METHODOLOGY FOR THE EVALUATION OF AIR DEFENSE SYSTEM EFFECTIVENESS

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Monterey, California

THESIS

METHODOLOGY FOR THE EVALUATION OF
AIR DEFENSE SYSTEM EFFECTIVENESS

by

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Methodology for the Evaluation of Air Defense System Effectiveness

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ABSTRACT

Recent literature in military operations research has indicated a continuing requirement for methodology to determine the military worth of existing systems and to forecast that of proposed systems. This thesis examines the factors upon which system effectiveness depends and develops methodology for the evaluation of air defense systems. Previous methodologies are reviewed and evaluation weaknesses and methodological issues are examined. Methodological difficulties of air defense evaluation are discussed and conclusions and recommendations are presented.

TABLE OF CONTENTS

LIST OF FIGURES

I. INTRODUCTION

The military value of a weapon system has long been of interest to decision makers who are charged with the responsibility of developing and fielding such systems. Consequently, a major methodological problem of military operations research (see, for example, [Ref. 25] or [Ref. 12]) is how to determine the worth (i.e., the effectiveness of a system according to some scale) of existing systems and how to forecast that of proposed systems. The subtle difficulty of this problem and its importance in military operations research is clearly indicated by its continuing discussion at Military Operations Research Symposia (see Ref. [22]), in open literature [Ref. 17] and in monographs [Ref. 19].

This thesis is concerned with the development of methodology for the evaluation of air defense systems. Prior to developing this methodology it appears worthwhile to critically review previous methods used in air defense evaluations and to examine the factors upon which system effectiveness depends.

Precise definitions can significantly assist the organization and communication of ideas and information. To facilitate the development of methodology for evaluating air defense system effectiveness, there are several terms which require definition. Ackoff [Ref. 1] defines methodology as

the study of scientific methods, which has as its objective the improvement of the procedures employed in the conduct of research. The importance of methodology is primarily the establishment of a standard to be applied as a means of controlling research.

Reference 44 defines the noun evaluation as: "The appraisal or determination of worth, value...." There are two connotative elements of evaluation for purposes of this thesis: first, appraise or determine implies an action pursuant to a result and second, worth or value implies a result.

Likewise, Reference 44 defines a system as: "a combination or arrangement of parts, elements...into a whole according to some rational principle." Extending the definition to the term air defense system yields a working definition for this thesis; an air defense system is the combination of tactical units, equipment, logistics, command control and communication (C^3), and other interrelated forces (ground or air) that are determined by the specification of a precise organizational level (i.e., battery, battalion, brigade, region).

In addition to the terms mentioned previously, system effectiveness must be defined. Reference 35 provides the definition of system effectiveness used herein: "...the extent of success to which the system may be expected to achieve a set of objectives." This definition depends upon three key elements ("the extent of success", "the system",

and "set of objectives") which will be developed in detail in Section III.

In this thesis the definitions above will be used in the following manner: (1) methodology will be the methods of control or standards for research; (2) an evaluation will mean an appraisal of the military worth of an air defense system; and the definitions of air defense system and system effectiveness will be used as defined, with the qualification that system effectiveness is assumed to be one of the primary means for appraising system worth.

There are several reasons for further developing methodology for evaluating air defense effectiveness. One reason, discussed in Section II, is that many previous efforts were primarily concerned with equipment, yet it is known that equipment alone cannot determine the outcome of a conflict. Rather, the outcome depends greatly upon the manner in which military equipment is deployed and operated to provide a coordinated air defense effort. Likewise, a successful outcome is relative to an opposing enemy force with its own objectives and tactics. Success also depends greatly on the combined effects of different forces using different equipment under the stress of combat. This means that broader aspects than merely hardware must be considered in order to evaluate system effectiveness.

Current reductions in the personnel strength of the Armed Forces lead to another reason for the development of system effectiveness methodology: reductions in manpower while

maintaining a high level of combat readiness and capability inherently suggests the need for more effective employment of available assets. This is especially true for Army Air Defense assets, where some of the older equipment has been deactivated and the remaining equipment must be evaluated for possible changes in mission and disposition.

Lastly, the increasing cost of developing and fielding new weapons requires better information concerning their possible military value. It is unlikely that future systems will ever be purchased in peacetime without a detailed evaluation of potential military value obtained from the new hardware.

This thesis was motivated by the shortcomings identified in other evaluations (Refs. 5,28,30,43,45) that were examined by the author and by the current interest in evaluation methodologies by the defense establishment. The approach to developing a methodology for air defense system effectiveness is based on the concept of system effectiveness that has been used in other areas [Ref. 25] and the major factors on which this depends [Ref. 17].

The determination of a military system's effectiveness is a key task in the defense planning process. A system's effectiveness is a criterion for comparing alternatives in, for example, the system acquisition process. The quantification of system effectiveness is a difficult task, and a critical one: the wrong quantification of system effectiveness

is tantamount to an incorrect planning decision. This thesis seeks to develop a comprehensive system effectiveness methodology with which the many and diverse factors upon which system effectiveness depends may be identified and systematically integrated into a realistic appraisal of system worth.

Section II provides a critical review of some past and current evaluation methods and identifies some of the weaknesses and methodological issues that must be overcome. Section III identifies the major factors upon which system effectiveness depends and shows how these are related to each other.* This system effectiveness methodology is analyzed in Section V ; followed by conclusions and recommendations in Section VI .

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*The reader may wish to refer to this section initially if the terminology in preceding sections is not familiar.

II. BACKGROUND

In Section I the terms evaluation and air defense system were defined and it was noted that system effectiveness is a difficult but important measurement when determining the worth of an air defense system. By contrast some of the past efforts to appraise system effectiveness have not been very successful.

A. METHODOLOGICAL HISTORY

It is interesting to note that for many years air defense evaluations were based solely upon the single shot kill probability of a missile or gun against typical threat vehicles [Ref. 30]. Reference 35 discusses the single shot kill probability (P_{ssk}) as a function of the impact point distribution and a lethality function ($\ell(|x|)$ = P[target killed|round lands distance $|X|$ from the target]). In the one dimensional case

$$P_{ssk} = \int_{-\infty}^{\infty} f_X(x;\mu,\sigma)\ \ell(|x|)\ dx$$

where $f_X(x;\mu,\sigma)$ is the impact point distribution and $\ell(|x|)$ is the lethality function. This measurement was considered a useful tool because it had a degree of predictive capability that the decision maker could use as an adjunct or a replacement for the qualitative judgements he previously

relied upon. But the use of single shot kill probability neglected vital engagement functions such as acquiring, tracking and identification. This oversimplified use produced overly optimistic results. Additionally, there was the problem of ascertaining what a typical threat was in relation to the missile or gun. Even when the evaluation was conducted as a system engagement and the accompanying threat was described (usually in terms of a nominal aircraft), the information provided to the decision maker was no more than a compounding of probabilities where the probability of a successful engagement (P_{se}) might be described by

$$P_{se} = P_{acquire} \times P_{track} \times P_{identify} \times P_{ssk}$$

Next, air defense systems were evaluated by determining the cumulative kill probability against a nominal enemy vehicle with a flight path from the system engagement envelope to the weapons release line for a target [Ref. 30].

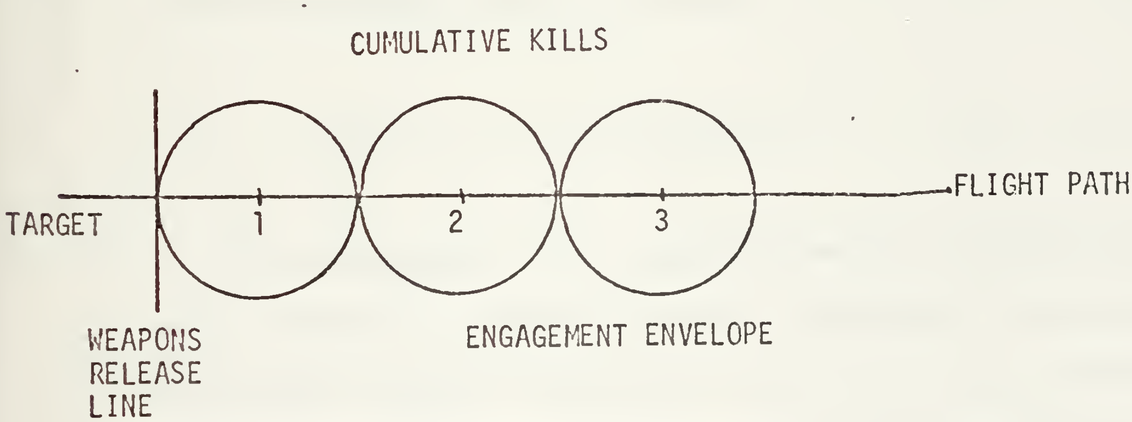

FIGURE 1

For example, consider Figure 1 above where fire units 1, 2, and 3 are each capable of firing twice on the penetrator. Assuming independence between rounds and varying hit probabilities (p_i) the cumulative probability of hitting the target at least once with n rounds is

$$P_n(1) = 1 - \prod_{i=1}^{n} (1 - p_i) \quad , \quad \text{for } i=1,2,\ldots,n \text{ [Ref. 35].}$$

When independence of the effects of successive rounds is not valid this approach is inadequate. An alternative would be to use the Markov property [Ref. 35] where the i^{th} round depends only upon the $i\text{-}1^{st}$ round; if p is the probability of a hit on the first round, then the probability of no hits with n rounds is

$$P_n(0) = (1 - p)[P(m|m)]^{n-1}$$

where $P(m|m) = P$ (miss with i^{th} round|miss with $i\text{-}1^{st}$ round), and the probability of at least one hit with n rounds is

$$P_n(1) = 1 - (1 - p)[P(m|m)]^{n-1} \quad , \quad \text{for } n \geq 1 \text{ .}$$

This quantity (i.e., cumulative kill probability) is a good measure of system firepower capability but does not adequately reflect the true mission of an air defense system which is to protect friendly assets by neutralizing enemy

aircraft. This is effectively a classic example of using the wrong criterion for assessing system effectiveness: the true mission of air defense is not to shoot down hostile aircraft but to defend friendly assets. Other methodological weaknesses were that in such an evaluation it was assumed that the threat flew a level constant speed path through the defense and that the vehicle would continue towards a higher priority target rather than engage the air defense fire unit.

Many other measures have been used to evaluate air defense and each has provided additional information to the evaluation effort and each has also provided difficulties when used in an evaluation.

One such measure is the mathematical expectation of targets killed or damaged. Reference 38 defines the expected value (mathematical expectation) of a discrete random variable X, with probability density function p(x) as the summation

$$E(X) = \sum_i x_i \, p(x_i) \quad .$$

This is an indication of what results might occur on the average if a conflict were repeated a large number of times. The main weakness in this measure is that it fails to tell how much variability there is about the average. Thus, we fail to know whether a radically different outcome is likely.

For example, if Markov-dependent fire is assumed, the expected number of rounds ($\bar{n}$) to kill a target is expressed by

$$\bar{n} = \frac{P(h|h) - p}{P(h|m)} + \left[\frac{1 + P(h|m) - P(h|h)}{P(K|H)\ P(h|m)} \right] ,$$

but the expected number of rounds ($\bar{n}$) gives no indication of the "scatter" around $\bar{n}$ that might occur when concrete realizations are obtained.

Expectation is less than adequate from the enemy point of view also, because the expected number of sites suppressed would not be sufficient information to determine whether or not a gap or corridor existed in the defense. For example, consider the missile units (x) and the raid corridor (arrow) depicted in Figure 2. If the expectation was three missile units suppressed the enemy would not be able to determine whether or not the corridor was clear because E(X) would not indicate which three were suppressed.

EXPECTATION EXAMPLE

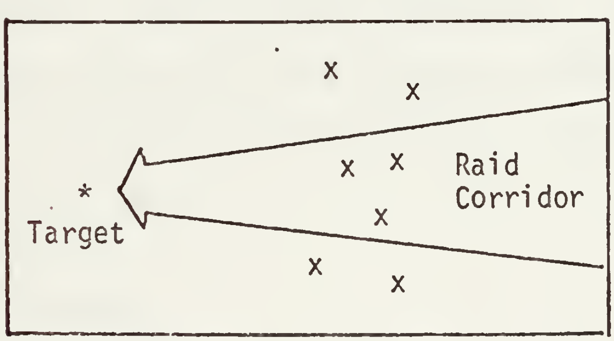

FIGURE 2

Additional measures of effectiveness that were introduced and used in air defense evaluation were discussed in a study [Ref. 30] which considered:

- the number of air defense systems required to provide minimum coverage over a given area and against a specific threat vehicle.
- the number of air defense systems to limit damage inflicted to some predetermined value or to the point where adding more defense resources results in diminishing returns.

A general evaluation methodology for air defense systems would enable an analyst to determine the applicability and point out the possible weaknesses of those measures listed above.

Likewise, the two measures which deal with the "number of systems" may not be the most appropriate means to evaluate a system. Selection of an inappropriate system may lead to suboptimization if the system is too narrowly defined, and if defined broadly it may not be feasible to obtain a valid analytic expression to evaluate the system [Ref. 16]. This point is illustrated in a recent thesis dealing with air defense missile storage, where several different warheads were available. The storage problem was evaluated at the firing battery level and the results indicated that the battalion or brigade levels would have been the proper system to select [Ref. 28].

B. RECENT METHODS

One of the methodologies which has gained a great deal of popularity and use was proposed by the Weapon System

Effectiveness Industry Advisory Committee (WSEIAC). Effectiveness is discussed in terms of three major factors — availability, dependability and capability.

The general form of WSEIAC effectiveness is given by the following equation [Ref. 30];

$$\text{Effectiveness} = A \times D \times C$$

where A, D, and C are the factors pertaining to availability, dependability and capability. Availability depends on the condition of the system at the outset of a mission; dependability describes the system conditions during a mission; and capability describes the lethality or ability of the system to accomplish its mission, given the system condition during the mission. To apply the method to a given mission for a particular system the system states (i.e. fully operational, degraded operation, out of action, etc.) must be related to availability and dependability measures and then the capability measure relates the system state to the alternative mission outcomes. This works well in the case of some air defense systems where the availability and dependability may be influenced by several components. However, for other military systems this approach may be of limited use when one of the key factors of the general expression dominates the development of effectiveness or effectiveness is desired at a level above an individual weapon situation. For example, a rifle has an almost certain probability of being available

and dependable, which leaves the capability as the factor dominating the effectiveness value. With more complex systems the factors become more difficult to model but the concept can still be used.

An example of how this might be applied to a simplified air defense situation might take the following form,

$$\text{Effectiveness} = A \times D \times C$$

where

$A = f(\text{time between failures, time to repair})$

$D = f(\text{detection, transfer, evaluation})$

$C = f(\text{missile launch, missile flight, lethality})$

and further refinement might lead to the equation,

$$\text{Effectiveness} = A \times P_d \times P_k$$

where

A = operational availability

P_d = probability of acquisition evaluation and transfer of a target

P_k = launch reliability × missile flight reliability × missile lethality

A relatively simple example such as the one above becomes increasingly complex when degraded modes of operation, multiple mission requirements, in-mission repairs and other considerations are included. The wide use of this method and the popularity it currently enjoys is because it is conceptually

applicable to a large number of systems and situations but computational extension of this method is difficult. The difficulty is readily observed by considering the transition between system states caused by failure rates and in-mission repair rates. Consider a simplified radar with four operational and non-operational modes (x_1, x_2, x_3, x_4) and with two circuits (1, 2). Assume circuit 1 as a circuit whose failure makes the radar out of action and circuit 2 degrades the radar when it fails but does not put the radar out of action. The differential equations of state transition rates for this single piece of equipment would be

$$\begin{bmatrix} \dot{x}_1 \\ \dot{x}_2 \\ \dot{x}_3 \\ \dot{x}_4 \end{bmatrix} = \begin{bmatrix} -(f_1+f_2) & r_1 & r_2 & 0 \\ f_1 & -(r_1+f_2) & 0 & r_2 \\ f_2 & 0 & -r_2 & r_1 \\ 0 & f_2 & 0 & -(r_1+r_2) \end{bmatrix} \times \begin{bmatrix} x_1 \\ x_2 \\ x_3 \\ x_4 \end{bmatrix}$$

where f_i = failure rate for i^{th} circuit, $i=1,2$

r_i = repair rate for i^{th} circuit, $i=1,2$

A more complete discussion of this example is given in Reference 45.

Consider a weapon that has been evaluated according to the WSEIAC method. If it is desired to extend the evaluation to a higher system level then a choice must be made to aggregate the weapon measures to include several systems,

each with its own set of measures, or to reformulate the task strictly in terms of the parent system. The first case results in an extremely difficult and perhaps intractible situation computationally whereas the latter case may generalize the results at the system level or may not use system results at all.

The need to process and store large amounts of information, when evaluating complex air defense systems, has resulted in the increased use of simulations. One such simulation is the Tactical Air Defense Computer Operational Simulation [Ref. 5] (TACOS II) which simulates conflict between a large number of air defense systems and a corresponding large force of penetrator vehicles. It includes an environment and terrain interaction and conducts a conflict situation, keeping track of all critical events. The expressed objective of TACOS II is to gain insight through total defense effectiveness evaluation in support of force deployment, doctrine and allocation analyses (Figure 3). Additional utility is gained through the use of TACOS as an input into a larger evaluation, Deterministic Mix Evaluation, Worldwide (DMEW) [Ref. 40].

TACOS II is a powerful tool which does provide a great deal of information, but there are difficulties associated with it that leave some unanswered questions with respect to air defense effectiveness. One such difficulty is the lack of an interaction with friendly interceptors. In an area of consideration that is approximately 1600 km × 1600 km, where

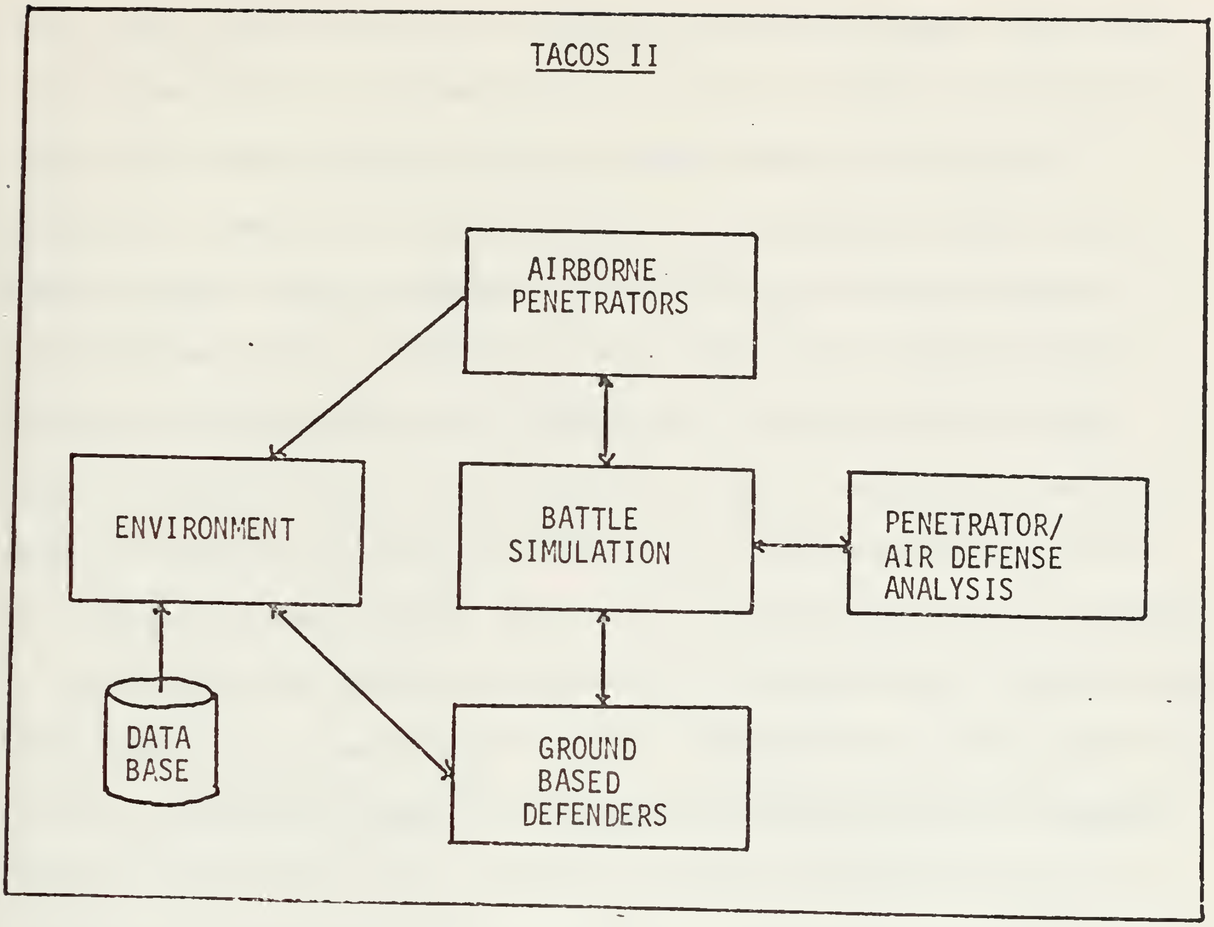

FIGURE 3

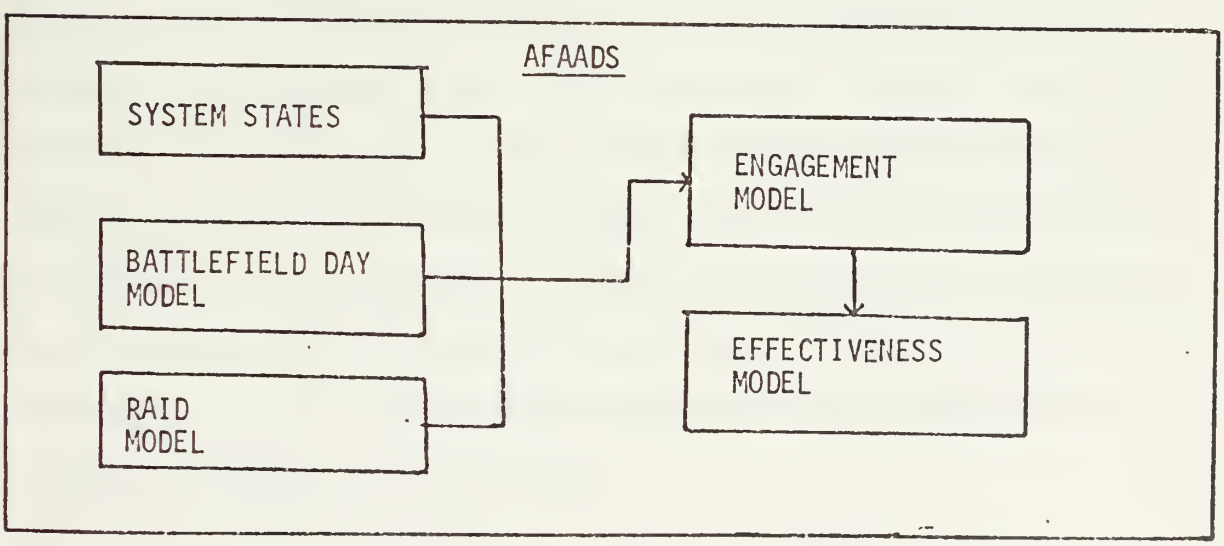

FIGURE 4

more than 2000 penetrator vehicles are postulated, one must also postulate the interaction of every friendly interceptor that can become airborne which TACOS does not consider. Similarly there is no interaction with ground combat forces which affect the deployment of divisional and Field Army Air Defense assets, which in turn affect the targeting and tactics of the penetrator vehicles. The point to be made here is the fact that a technically sound assessment model fails to yield an accurate picture of system effectiveness if it is exercised under the wrong or incomplete circumstances.

A recent air defense evaluation (although not a simulation) which reflects some of the recent methodological developments is the Parametric Study of Advanced Forward Area Air Defense Weapon System [Ref. 45] (AFAADS) which like TACOS II is composed of submodels (Figure 4), but is restricted by design to forward area air defense systems although its methodology could be used to evaluate missile systems as well. AFAADS incorporated the WSEIAC scheme in the form of matrices to describe operational states and substates. Using these matrices in conjunction with a descriptive battlefield day model, raid model, engagement model, and effectiveness model, AFAADS generally provides a useful and productive evaluation. The distinguishing feature of this study is the approach of providing a set of effectiveness results corresponding to possible enemy attack options.

In general, the trend in air defense evaluation has been from one initially depicting a restricted, simplistic tactical situation, characterized by a single value describing system capability, to one depicting a broadly defined conflict, described by a set of results related to a corresponding set of enemy options. In spite of the developments in the area of air defense evaluation, the conceptual weaknesses which still exist raise doubts concerning the extent to which current methodologies can accurately analyze air defense forces.

Critical review of the previous evaluations indicates that current methodologies fail to account for some important considerations related to air defense systems. Failure to select the appropriate system, the right criteria, or an incomplete description of the circumstances surrounding the operation of an air defense system indicate the need for a systematic means of identifying such facets. The methodology proposed by this thesis is motivated by the need to address these considerations and is intended to provide a logical approach to them.

There are weaknesses associated with any military evaluation and air defense evaluations, both of systems in acquisition and of existing systems, are no exception. In general, the weaknesses associated with air defense evaluation can be related to two broad categories: (1) input deficiencies and (2) methodological questions. These will be discussed in Section II C,D which follows.

C. INPUT DEFICIENCIES

The most refined air defense methodology will not improve the usefulness of results that are based on data that is suspect or cannot be verified. The first priority of any evaluation must be to consider what data is available and how it can be best used to support the evaluation task.

A concurrent issue related to input data is the consideration of developing a methodology which matches availability and credibility of the input data. A sophisticated methodology for which input data cannot be provided or generated has no utility. Hence the user and the analyst must closely coordinate the input formulation stage [Ref. 25], to bridge the gap and relate the detailed system characteristics or measures of performance to a measure of mission success. Few techniques exist which adequately accomplish this task.

The scenario is a key element because it drives the entire analysis. When the scenario is altered by changes in the mission or objectives the analysis may have greatly varying results. As an example consider the possible difference in results, casualties in this case, that would occur if a defensive force that was entrenched and ordered to hold its position, were given a different objective such as to delay the attacking force trading space for time. Clearly we would expect the delaying force to receive fewer casualties than the force which attempted to hold its position and not yield to the attacker. The implications of a scenario which is

designed without consideration of an important tactical relationship is even more critical. In the case of most air defense evaluations the failure to include friendly interceptor aircraft has to be regarded as a critical weakness when their effect upon enemy forces and enemy tactics is considered in addition to their contribution in support of the accomplishment of the friendly mission.

Another often encountered scenario deficiency is the failure to adequately incorporate friendly land combat forces. Air defense assets assigned to divisional units are primarily low altitude, short-range weapons, and the disposition and deployment of the land combat forces greatly affects the location and effectiveness of the air defense weapons. This may result in an unrealistic scenario since the type of division may also affect the target priorities and the sortie allocations of the enemy force. Failure to consider either scenario deficiency may result in an unrealistic scenario which in turn generates evaluation weaknesses.

An evaluation often includes many systems each possessing different system characteristics. But system characteristics can only assist the measurement of system performance. It is the system as a whole which has an effect on individual or collective evaluation outcomes. This is especially true with air defense units because there are a large number of dependent measures of performance which contribute to mission success. Instead of a single vehicle with specified armament

and ordnance, it might be necessary to consider a system which depends on several vehicles, several radars, processing equipment and each round associated with its associated launcer.

There are many other input deficiencies that contribute to evaluation weaknesses such as target detection cases in which weather and terrain masking and the lack of operationally oriented data create problems. Likewise, new systems, techniques and tactics involving design data rather than historical or operational data create weaknesses and evaluation problems during system acquisition. But even thorough consideration of input data for a carefully constructed methodology has not eliminated the persistent (i.e., those that one cannot eliminate) uncertainties associated with the input deficiencies discussed above. Scenario deficiencies and performance measures that are dependent upon external factors (i.e., performance depends on threat, environment, etc.) can be addressed by a methodology which considers the different missions and tactical relationships that are present in combat. This consideration is addressed by the proposed methodology as a part of system description (Section IV A) and system mission (Section IV B). Although persistent uncertainties may remain, the effect may be reduced by considering a range of values to observe the variation in outcomes. Sensitivity is also approached as a methodological issue later in this section.

D. METHODOLOGICAL QUESTIONS

In addressing methodology questions related to evaluation weaknesses an earlier statement relating carefully developed methodology to faulty input can also be approached from the opposite point of view: ineffective methodology can restrict the usefulness of carefully developed, operationally oriented input data. One of the most common methodological weaknesses is the use of a one-sided methodology when combat is necessarily a two-sided question. A one-sided methodology describes the situation where one of the opposing forces is fixed and the other force changes combat options or weapons and force mix to evaluate the alternatives. An example, which occurs frequently, is the evaluation with opposing tactics and systems described by fairly accurate input data. Then the friendly air defense systems and tactics are altered to compare alternatives without changing the targets or flight paths or priorities of the opposing force. This is clearly an evaluation weakness because when one force changes its systems or tactics, it has done so usually as a result of an interaction with the opposing force; the same interaction applies in principle, if not in detail to the opposing force. The interaction is continuous and difficult to handle therefore many times it is neglected to keep the problem more manageable. Failure to include the change in enemy tactics, that is based upon a change in the perceived threat, is a methodological weakness. The importance of a two-sided

evaluation can be seen by considering the determination of optimal allocation of tactical resources for an attacker and a defender. Assuming that the allocation decision is made simultaneously* by both decision makers without knowledge of the opponent's exact course of action but taking into account his possible allocations, this problem may be formulated as a zero-sum game problem. This problem (in particular its analytic formulation) is considered in Appendix A. It should be clear from perusal of this simple example that potential enemy courses of action must be considered in air defense evaluations and are an integral part of the system effectiveness study process. In other words, the return (payoff) to each combatant depends on not only the friendly strategies but also the enemy strategy. The final decision to have a one-sided or two-sided evaluation will depend on the objectives of the evaluation, but, if not included, the reasons for accepting such a weakness should at least be documented.

Another methodology question which should be discussed is the aggregation of submodels. One extreme would be to employ a few highly specialized submodels aggregated into an overall system model in the way TACOS approaches the problem. The other extreme would be a single high resolution model which describes and analyzes the entire tactical situation. The

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*Actually, one need only assume that, for example, the attacker determines what his strategy should be without knowledge of the exact courses of action to be followed by the defender.

highly aggregated method provides flexibility, to include varying situations, and specialization, to focus on a critical area, in a methodology but the user must deal with submodel compatibility by functionally integrating the information provided by each. The single unified model has methodologically solved the integration problem, usually at a higher initial cost, but it is less flexible and time consuming to re-program for additional contingencies [Ref. 3].

All evaluations are necessarily limited to a maximum number of systems and scenarios either by economic or design considerations. Some of these limitations are handled by using assumptions, which in turn, generate a number of "what if..." questions. Sensitivity analysis can enhance evaluation results by dealing with these questions. The extent of sensitivity analysis should be considered methodologically in the development stage where it can be related to evaluation objectives and be designed to include the most critical, or first order, effects [Ref. 25]. As an example, consider a system which has an important characteristic of performance, time to acquire a target, that has a wide range of possible values. If the expected value were used to describe time to acquire, when it was known to take on many values, there would be a finite probability that the true value was significantly different from the expected value. However, if a range of values were used, an analyst could determine the sensitivity of the results to changes in that range of

input values. If sensitivity is considered methodologically in the formulation stage of an evaluation, the "what if" questions can be incorporated into the overall evaluation plan.

A large amount of uncertainties exist when combat is evaluated, but many studies and evaluations are deterministic and cannot adequately consider the risks associated with the evaluation results. Consider the simplified WSEIAC example earlier in this section. If the A, P_d, and P_k values were deterministic quantities they would provide no measure of risk associated with the effectiveness result. The methodological question of whether or not uncertainty should be included is more easily answered than the question of how to provide for it. It is desirable to reflect uncertainty if possible, since it provides the user with more meaningful results (i.e. an assessment of risk) to assist the decision-making process. When included in the evaluation, uncertainty may be incorporated as a part of sensitivity analysis where probabilities are assigned to the input values for a single iteration. Then, combining the results of all iterations (runs), a distribution for the outcomes could be developed. A more direct approach is to model uncertainty as an integral part of the methodology through stochastic modeling or for more complex systems (such as air defense systems) Monte Carlo techniques might be used [Ref. 25].

III. SYSTEM EFFECTIVENESS

A. PLANNING DECISIONS

Throughout the life cycle of military systems a particular piece of equipment or hardware is continually evaluated to insure that it meets the needs of the service by performing the tasks for which it was designed. On other occasions an analyst is called upon to evaluate different systems and to determine which is the "better" system. Many different evaluations may be developed or used during this period but each has as its goal to provide information which will assist the decision makers. Over this ten, twenty, or thirty year period planning decisions are made based upon the evaluations of the system. The types of decisions may vary but the evaluation will still be keyed to the system.

Decisions are continually made during system life, initially as a factor of system design and later as a part of system modification and system improvement. Whether it is the system or a specific piece of hardware, the requirement is to compare and evaluate alternatives to provide a basis for the decision-making process. Planning decisions are involved with system design and development. Design decisions are made throughout the pre-production phases and also during prototype development. Other planning decisions are considered during procurement and production of a system and at this stage planning decisions are of particular importance since

it is necessary to determine how many systems to produce. The planning decisions which are considered during the operational life of the system are based on weapon system evaluations. A frequent criterion used to conduct weapon system evaluations and assist in planning decisions is system effectiveness. System effectiveness measurement provides a means of evaluating air defense systems in terms of how well the system meets its objectives.

B. ELEMENTS OF SYSTEM EFFECTIVENESS

Choosing the better system is a difficult task in the planning process. A system's effectiveness is used by analysts as the criterion for comparing alternative systems. If the effectiveness of a military system is considered to be the extent of success to which the system may be expected to achieve a set of objectives, then a conceptual definition has been formulated. Since this qualitative statement cannot easily be measured, a quantitative expression is needed that more precisely defines a system's effectiveness. This is done by developing an operational definition for the abstract concept, where an event (that can be measured) is chosen to represent the concept. Development of an operational definition must be accomplished by addressing the key elements upon which system effectiveness depends.

The key elements are "military" system", "set of objectives", and "extent of success". It is necessary to define clearly the system to be evaluated. This task is

often difficult because the system being evaluated may depend upon the operation of subordinate systems, adjacent systems or parent systems (Figure 5). For example, if we evaluate an air defense battalion the parent system might be an air defense brigade while the subordinate system would be the firing batteries which form the battalion. Similarly, if the brigade were the evaluated system, then the air defense region would be the parent system and the battalions would be the subordinate systems. It is often the case that we design systems to provide mutual interactive support and to operate as a subcomponent of a large system. Missile batteries, for example, interact strongly, which may be seen by considering the fact that they have overlapping zones of radar coverage and alternate primary search areas in the event that an adjacent unit is out of action. These same batteries, when aggregated into a larger system form a defense in depth based on the coverage provided by successive units. Gun systems also provide mutual support by sharing early warning information among the units and by their deployment in pairs which enables a weapon to reload or repair while another system provides protection. For this reason it is necessary to clearly define the system to be evaluated, since narrowly describing a system in terms of subordinate systems may lead to suboptimization problems and describing the system in terms of the broader parent system may also be misleading or make the analysis nearly impossible [Ref. 15].

SYSTEM RELATIONSHIPS

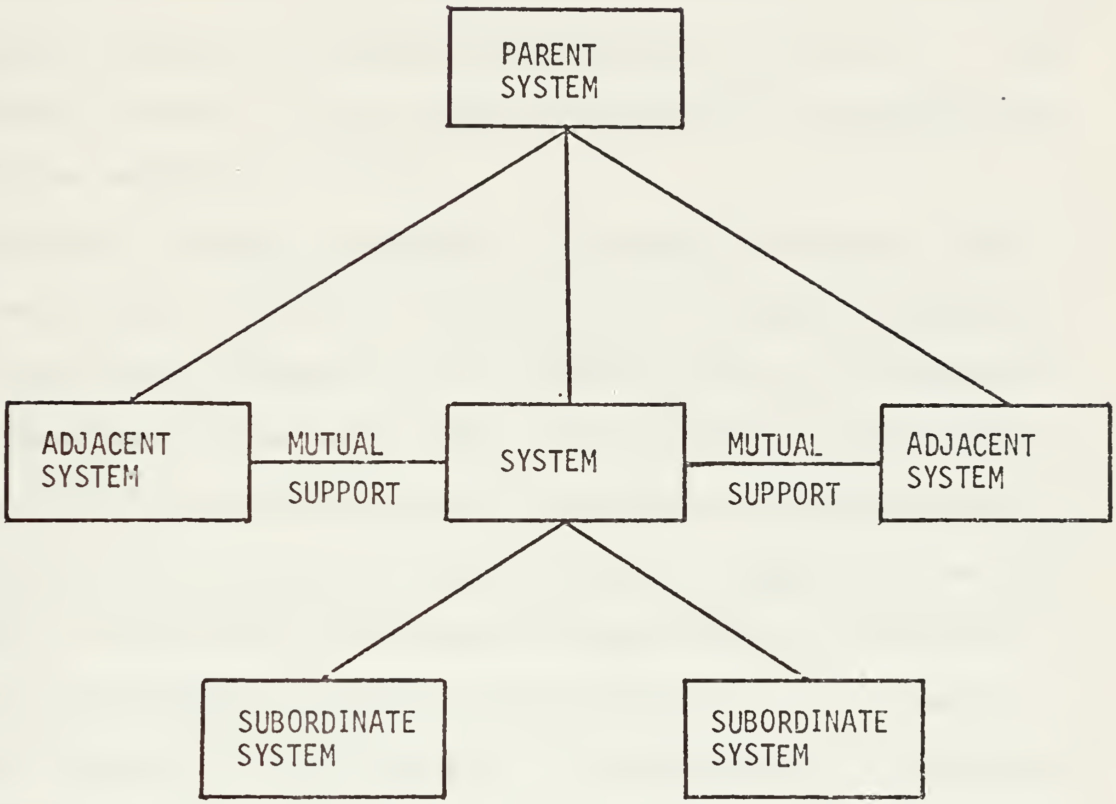

FIGURE 5

An essential part of defining the system to be evaluated is the description of the particular system and how it operates. Understanding how the system operates leads to a more reasonable set of system objectives which is another key element in developing system effectiveness (Figure 6). By operation we mean how the system mechanically performs and how it is employed or used.

Obtaining system objectives is another important task in the development of system effectiveness. These objectives are determined judgmentally by analysts and are based upon the best information available. This requires an in-depth study of warfare and a study of conflict to determine the key objectives of the military system in combat and how the extent to which the objectives are met might be measured. If it is possible to specify the mission in a clear and precise manner, the objectives may be determined by logically translating the system mission into a set of desired outcomes. Careful evaluation of each portion of the system mission may identify both explicit and implicit mission requirements. The explicit element of the mission is usually concerned with the overall objectives of the system, whereas the implicit element though not stated in the system mission, are objectives which must be accomplished in some measure to insure that the overall objective is achieved. For example, the localized defeat of an enemy force may be an explicit objective, but the attainment of that objective may implicitly involve

ELEMENTS OF SYSTEM EFFECTIVENESS

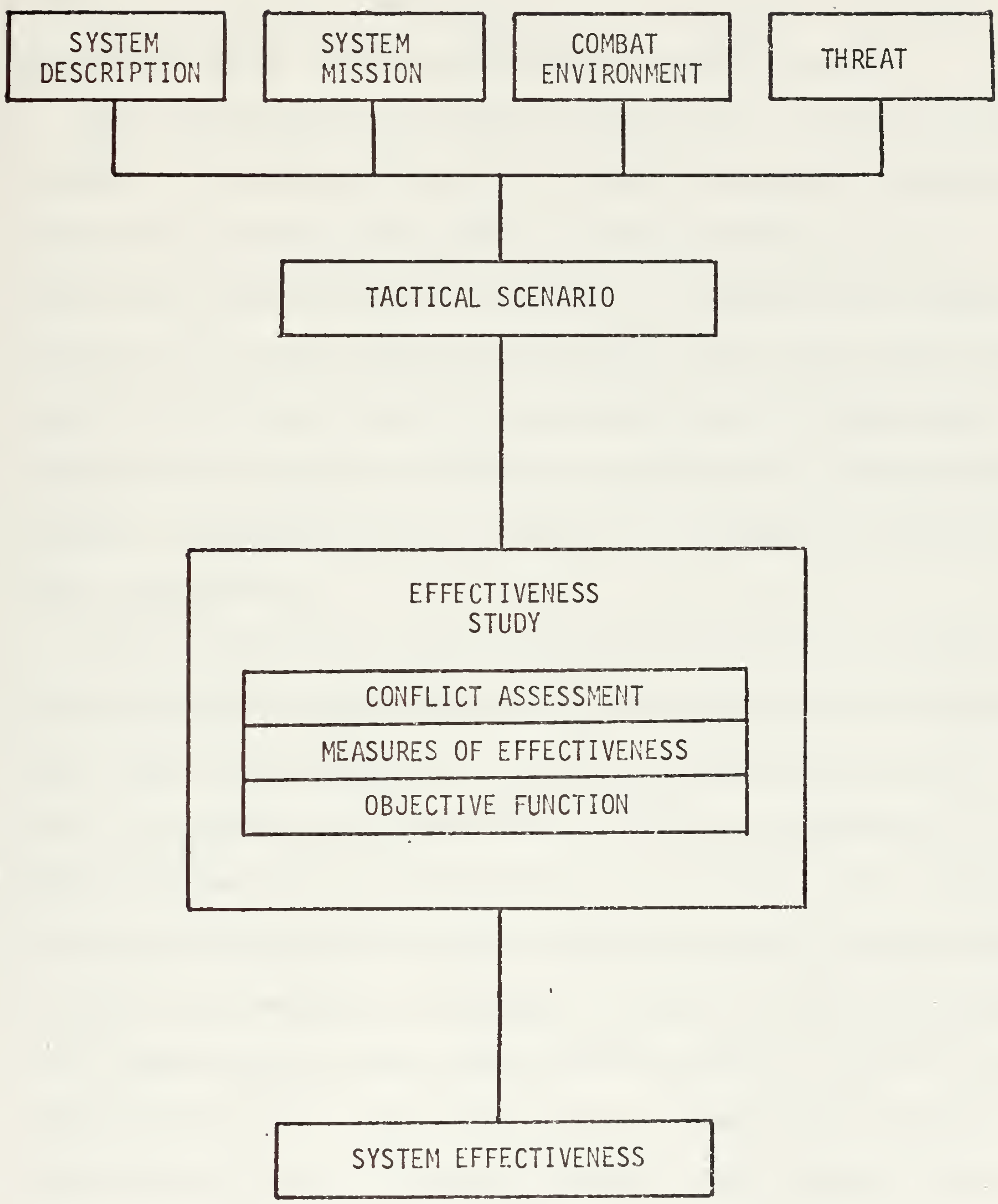

Figure 6

negotiating a river crossing and a certain minimum level of force attrition which were not specified in the mission statement. Therefore it is necessary to represent the system and its objectives operationally to provide a concrete situation that will stand for an abstract concept.

The translation of system mission into a set of objectives becomes a consideration of the level of detail. Successful development of the objectives depends greatly on how thoroughly the mission is analyzed. Combining the mission analysis with the system description and system definition should generally provide a reasonable set of objectives enabling an analyst to develop a qualitative effectiveness concept, especially if the nature of military conflict is well understood.

When a military system is defined and has a specific set of objectives associated with its operation it is assumed that there is a threat, or at least a postulated threat, that must be considered and any development or discussion of system effectiveness must be relative to the threat. The threat is of great importance because it generates the targets and tactics for conflict assessment (Figure 6); this is necessary if a concrete situation is to be developed in place of the abstract concept. The threat is also important because one objective of the air defense forces is to protect vital assets by neutralizing the threat. Additionally, the threat provides different types of threat vehicles, tactics, objectives and the timesequencing of these factors for conflict assessment.

Clearly, then, it is necessary to develop the known or postulated threat which confronts the system to be evaluated. The threat can usually be developed in terms of enemy objectives, forces and tactics [Ref. 17]. If a threat exists or is perceived to exist then forces are assumed to be associated with that threat and likewise the existence of forces implies that there are missions assigned to those forces. The missions may be related to threat objectives and the operation of the forces implies the existence of tactics which are used by the enemy.

The opposing forces, each with a method of operation and a set of objectives, have one element in common, namely, the combat environment where they both must exist and operate. Although the combat environment is common to both forces, its effect upon the opposing forces may be quite different, depending greatly on the composition of the forces and their individual objectives. Clearly, the terrain, weather, logistics and other combat environment factors will affect opposing forces in different ways. Once the combat environment is developed, and represented in conjunction with the opposing forces and their objectives we have the basic factors upon which system effectivenss depends.

Combat forces, their objectives and the combat environment provide the analyst with the ability to evaluate an abstract concept such as system effectiveness in terms of an event, the tactical scenario, which can be measured either

qualitatively or quantitatively. If in fact the tactical scenario does enable a concept to be represented and measured, then that concept has been operationally defined. The decision-maker or user must exercise careful judgement to determine the appropriateness of the factors upon which the tactical scenario depends. Of particular importance are those factors which describe the threat, because the objectives, forces and tactics of the opposing military systems are largely based upon synthesized intelligence data and perceived intentions. The tactical scenario may or may not be sensitive to these factors and the user must be cautious in determining their appropriateness. War gaming is one method in use which assists in determining the appropriateness of possible intentions.

The remaining portion of system effectiveness to be considered is the key element "extent of success". This element is evaluated by combining the results of an assessed tactical scenario with selected measures of effectiveness. Many means of assessment might be used to derive results from a tactical scenario, but often the "extent of success" and how to assess it is an unresolved problem in its own right [Ref. 17]. Parametric analysis of critical events might be one way of determining scenario outcomes. Another method would be to use assessment models or computerized routines of either a deterministic or a stochastic process to assess the conflict. Or perhaps quantified or qualified judgement

might assess other facets of the tactical scenario which do not lend themselves easily to other forms of assessment. The utility of operations research depends greatly on the appropriateness of the criteria by which the system is judged or compared. In determining the "extent of success" achieved by a system, selecting wrong criteria is tantamount to answering the wrong question. Similarly, using the wrong criteria can also result in an inappropriate assessment of system effectiveness. The desired criteria are those which enable an analyst to quantitatively experss the extent to which a mission requirements are attained by the system.

Measures of effectiveness may be drawn from two primary sources; they may be taken from doctrine or more likely derived from system objectives. When drawn from tactical doctrine we might expect the measures to be general in nature, since doctrine is based upon a broad and generalized view of conflict. On the other hand, those measures of effectiveness derived from system objectives are developed by quantifying previously conceived qualitative effectiveness concepts. For example, if the objective is to protect critical assets from enemy air attack it might be possible to quantify the effectiveness concept in terms of the number of assets that survive the attack and the cost to the enemy in planes of destroying one of the assets. If the result of quantifying these concepts is an expression of the extent to which specific system objectives are achieved, then, by definition, we have a suitable measure of effectiveness.

When the assessed results and measures of effectiveness are combined in an effort to describe overall system effectiveness, it is desirable to formulate an effectiveness function which will identify specific contributions to mission success. Consider the critical asset example once more; if we desire to formulate an effectiveness function we might very well desire a common measure. One such measure might be to use the dollar cost of assets and planes to obtain the function; other surrogate measures might be more meaningful such as tons of ordnance or the number of casualties. If the measures of effectiveness yield a quantitative expression of the extent to which system objectives are achieved and if the assessed results provide a quantitative description of significant variables then there exists an effectiveness function to describe the extent to which the system has achieved a set of objectives. This function will allow the analyst to calculate a value with which system effectiveness may be expressed.

In discussing system effectiveness the key elements of the definition were examined and related to system description, mission, threat and combat environment. The next task is to translate these four major factors upon which system effectiveness depends into an air defense context which follows in Section IV.

IV. METHODOLOGY FOR AIR DEFENSE

R. Ackoff has emphasized [Ref. 1] that the objective of methodology is the improvement of procedures and criteria employed in research. The emphasis in this section is focused on a systematic procedure for examining air defense systems in terms of the major factors of system effectiveness identified in Section III. The geometric aspects of air defense employment are illustrated in a two-dimensional representation of a three-dimensional problem. Short range air defense units (SHORAD), which are assigned to divisions are employed on or near the forward edge of the battle area (FEBA). Low-medium attitude air defense units (LOMAD) and high-medium attitude units (HIMAD) are less mobile than SHORAD units and are deployed in rear areas. This basic structure does not preclude mixing the assets (e.g. SHORAD deployed around an airbase) but does give a general representation of the disposition and relationship among air defense assets.

A. SYSTEM DESCRIPTION

Defining and describing the air defense system to be evaluated must begin with a decision on the system level. To define the system the overall goal of the evaluation should be known in general. An example might be to desire to investigate the effect two additional missile battalions would have on the enemy's ability to engage a given number of

GEOMETRY OF AIR DEFENSE EMPLOYMENT (SCHEMATIC)

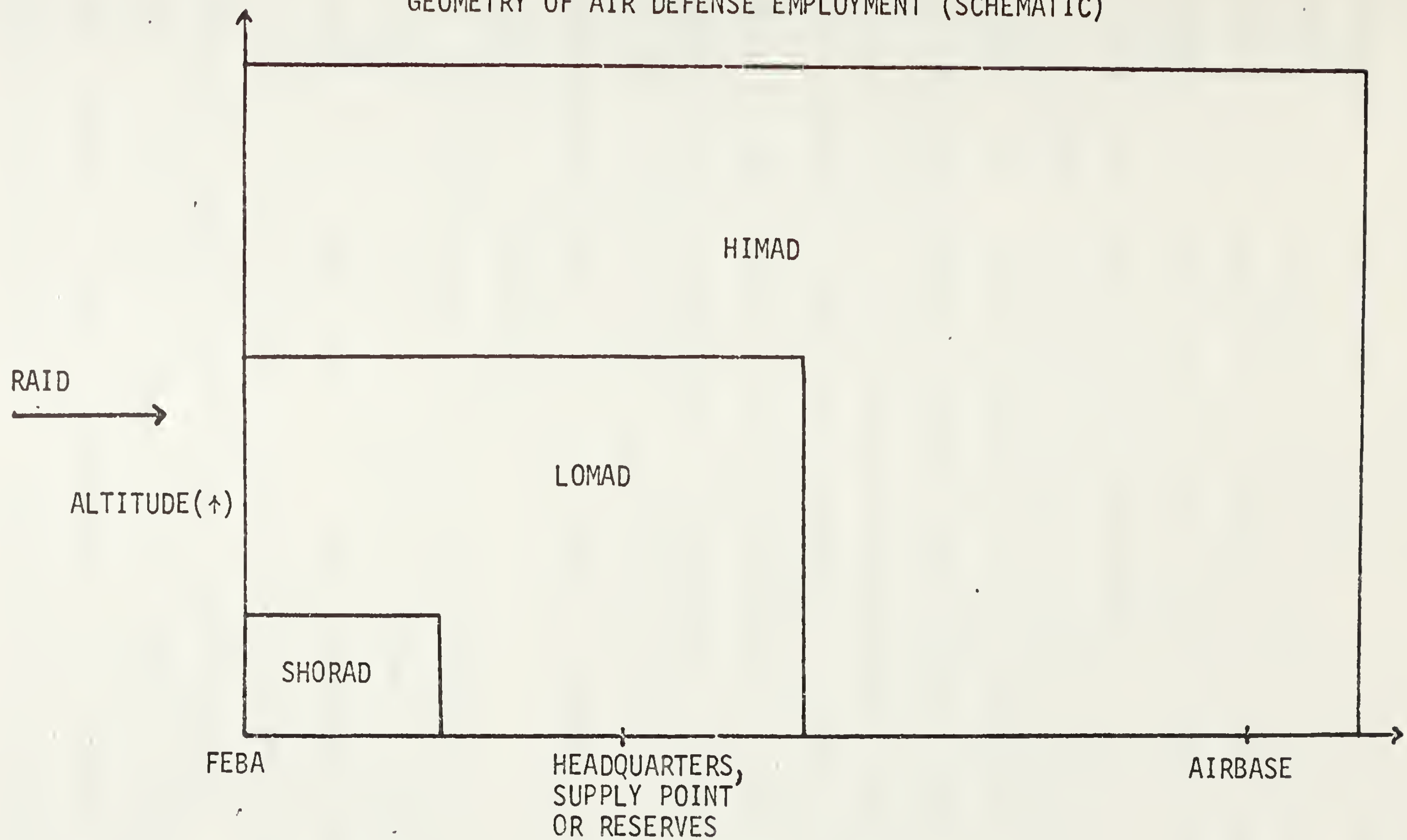

FIGURE 7

possible targets; or, perhaps, the effect that a new weapon might have in a similar situation. Referring back to Figure 5 this means that the system which is selected for evaluation determines the level of evaluation, the parent system and likewise the subordinate system. Identification of the system is an essential step because the parent and subordinate systems will affect many of the implicit objectives of the chosen system later in the evaluation.

Consider the missile storage problem discussed in Section I [Ref. 28]. It was pointed out that selection of the wrong system level produced results that did not answer the issue being addressed. In this case the results were inconclusive, which indicated there was a problem. In other situations the results might answer the wrong question or lead to the selection of an undesirable alternative. Another point to consider is the possible consequence that selection of the wrong system level may often lead to choosing inappropriate measures of effectiveness.

In selecting the system to be evaluated it is important to note that the air war which air defense assets must support is not a localized conflict. It is conducted over a broad front often with primary interest focused upon strategic objectives rather than tactical considerations. This must be kept in mind when selecting an air defense system evaluation level because failure to recognize this fact may lead to suboptimization problems. Motivation for evaluating over a

broad front with more general objectives may be generated by considering the attack-defense game described in Appendix A. This simple problem provides valuable insights to the allocation of air defense assets. The optimal allocation strategies for attacker and defender, respectively, are a concentrated attack at a randomly selected point of the defense, and a "proportional value" defense. Extrapolating this game theoretic result to the real world one would expect the attacker to saturate air defenses at selected points. Therefore at the battery or individual fire unit level (i.e., subordinate system) it would be expected that the attacker will overload or not engage individual fire units. Consequently, it does not appear appropriate to evaluate air defense at the fire unit level, since units here are either saturated or not engaged. Details of the attack-defense game are given in Appendix A.

Once the system is identified and selected, the system description task has begun since the level at which the air defense assets are defined influences the relative significance of some of the elements pertaining to system description (Figure 8).

There are many ways that a system might be described and Figure 8 depicts those ways which are most common to air defense systems. Vulnerability, flexibility and survivability are facets of system description which are often quite difficult to quantify but significantly influence the system

SYSTEM DESCRIPTION

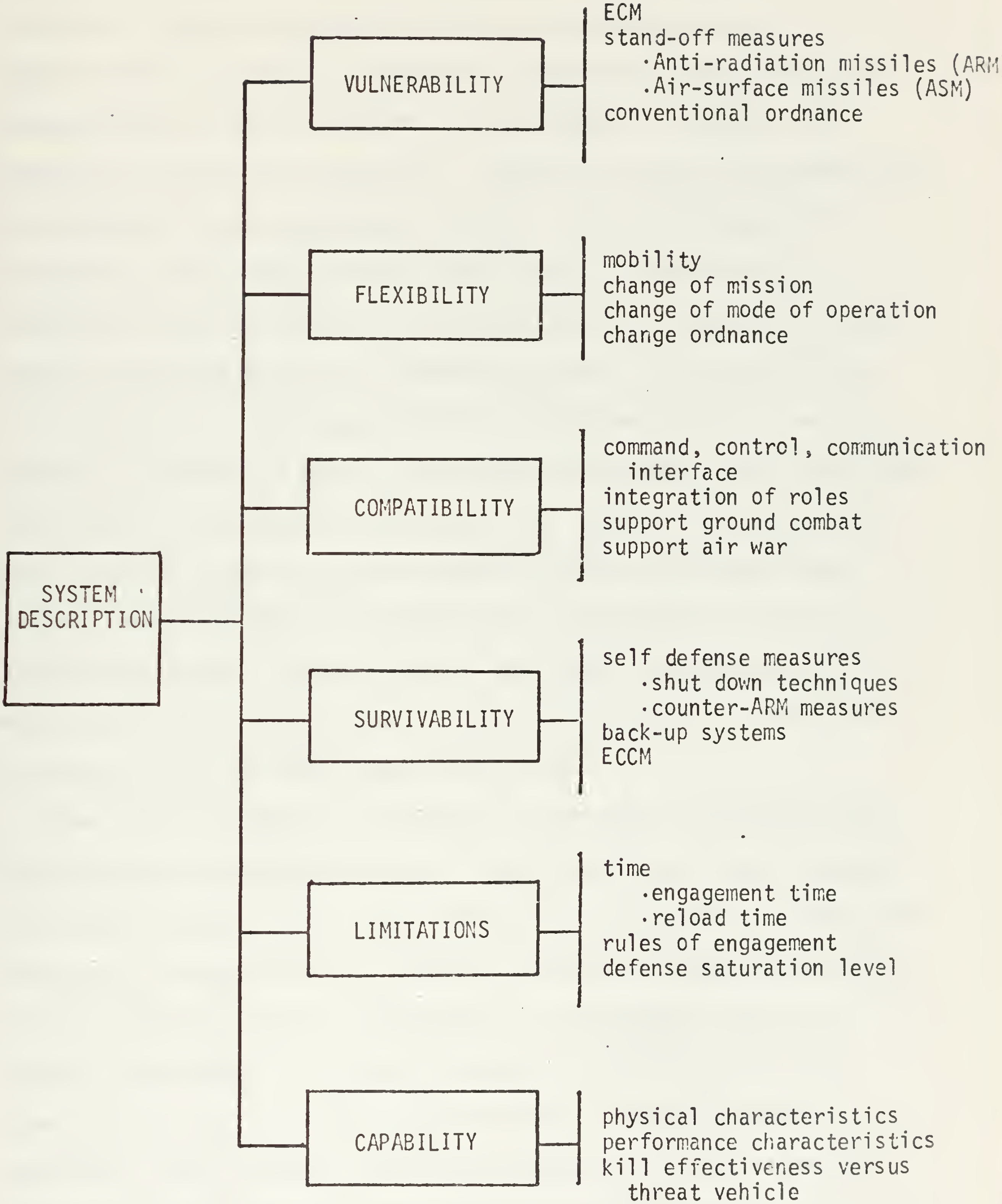

Figure 8

and its evaluation. The vulnerability of an air defense system is important because nearly all enemy courses of action would include air defense suppression, which will be assumed here to mean damaged or destroyed in addition to jamming of electronic devices. Therefore system vulnerability to electronic countermeasures (ECM), stand-off suppression, using anti-radiation missiles (ARM) and air to surface missiles (ASM), in addition to conventional ordnance are all means of describing an air defense system. The flexibility of a system is a consideration in system description because changes of mission, locale, or mode of operation are realistic situations which must be accounted for since they influence other factors such as system capabilities and limitations. System survivability is a subtle but important portion of system description because there may exist force levels at which the entire air defense system is sensitive to the loss or survival of an additional fire unit.

The major elements of system description are capability, limitations and compatibility. Simply stated, these factors might correspond to what the system can do, what it cannot do, and how it relates to the overall conflict. Capability, that is described by system performance, is probably the most common indicator of a system because it involves the more quantifiable and available information. This is indeed an important part of describing the system but it can also be misleading if it is not considered in conjunction with

limitations and compatibility. The limitations of a system can have a significant effect on the evaluation of a system by the manner in which they reduce the system capabilities. Considerations such as engagement time, reload time, rules of engagement and saturation levels provide a measurable and realistic input to system description. Compatibility, unlike capability and limitations is much more difficult to quantify, yet it is a key ingredient which provides relevant information with which a system may be described. In a general sense, compatibility might be called the ability of an air defense system to interface with ground combat forces and air warfare assets and to support both. This consideration identifies the need to exercise effective command and control over the high, medium and low altitude roles assumed by the individual fire units and emphasizes the requirements for an effective communication interface.

A careful description of "the system", as outlined in Figure 8, will assist the analyst in formulating an effectiveness concept. This is necessary if a quantitative expression is to be developed as a part of an operational definition. Clearly, the system must be known in terms of the elements of Figure 8 if it is to be assessed in terms of its military value.

As an example of the system description factors that have been discussed consider the simplified situation in Figure 9 which depicts three fire units (A, B, C) with their indicated

DESCRIPTION FACTORS

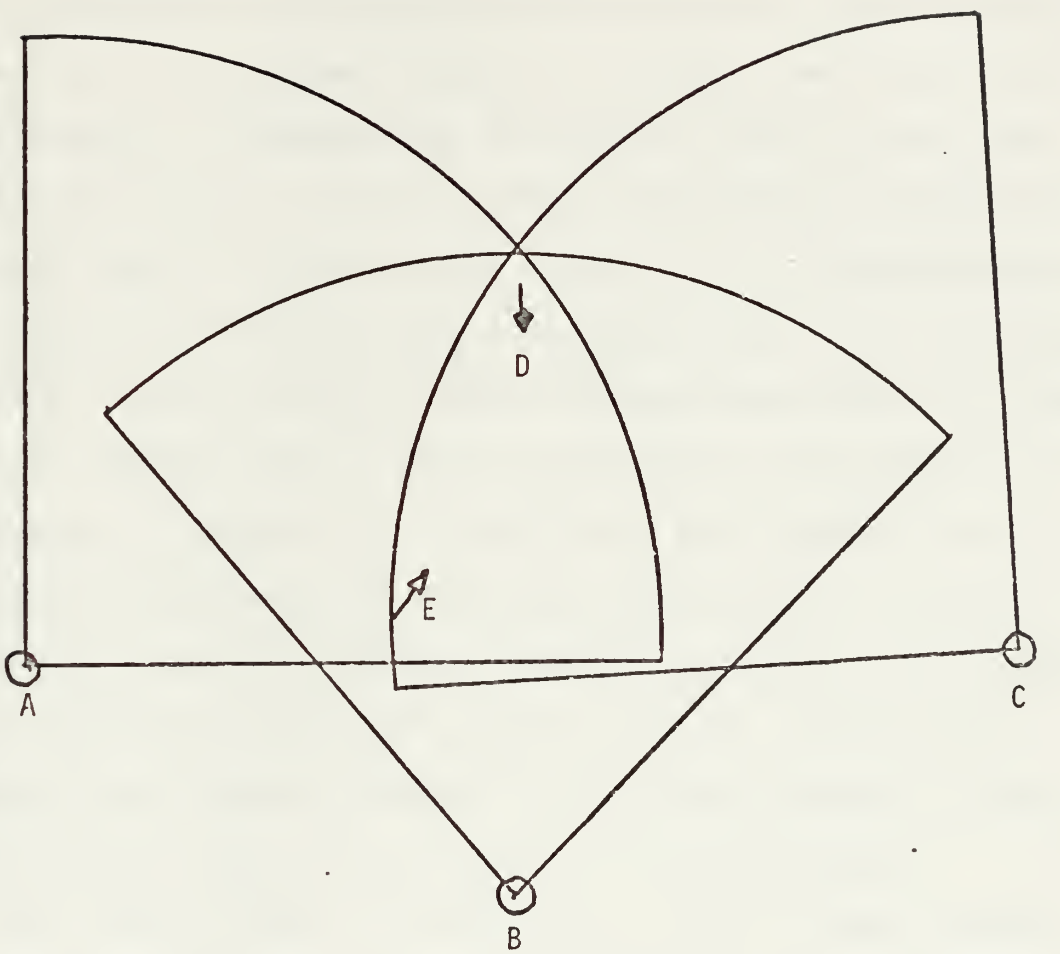

Figure 9

defense sector boundaries, an attacking aircraft (D), and a friendly interceptor (E). If the evaluation of this situation depended only upon system capability aircraft D might very well be a certain victim of either A, B or C. However, the limitations and compatibility factors can significantly alter even the simplest situation in such a way that it is unreasonable to address the outcome in terms of one round versus one plane. In realistically describing this situation we must know if A, B or C are operating or if one is reloading or another has insufficient engagement time. It is necessary to know if there exists a weapons restriction such as a hold fire or whether the vectored interceptor E has priority of engagement. Constraints of this type are realistic and certainly attenuate the simple consideration of aircraft capability versus air defense system capability. But these same limitations and compatibility factors also preserve ordnance and prevent accidents to friendly assets by coordinating the fires of units such as those depicted.

The actual extent to which any or all of these factors of system description should be included in an air defense evaluation will be determined by the evaluation objectives and the ability of the analyst to quantify the factors as meaningful input. But it is important to recognize that this is one portion of a study that usually can be quantified and care should be exercised not to overlook or hastily eliminate one of the factors as a source of system description.

A good example of system description is contained in the Advanced Forward Area Air Defense Study of Litton Systems Division [Ref. 45] where nearly every element described in Figure 8 was considered and quantified in careful detail. In general this is not done in such detail because comprehensive descriptions are costly. However, this study evaluated several evenly matched and highly competitive systems in an attempt to determine the most effective. Careful system description was essential in this case to adequately distinguish one system from another, whereas alternative study objectives might have resulted in a different approach to system description.

B. SYSTEM MISSION

The next key element in developing a system effectiveness framework for air defense is to translate the mission (given in Section IIA) of the system into concrete sets of system objectives. Recall the general discussion of system effectiveness where the mission was analyzed in terms of explicit and implicit mission requirements. In dealing with air defense missions consideration of both air warfare and ground combat requirements is important. There are also a wide range of missions that might be undertaken. The multitude of missions translates to an equally large number of system objectives and the usual problems of multicriteria decision making [Ref. 35].

An example of the difficulties involved with multiple criteria, consider the situation of three measures of

effectiveness corresponding to three alternatives, each evaluated with respect to three criteria. The alternatives and criteria provide nine situations to be addressed by each measure (3) resulting in twenty seven values for consideration. If one alternative fails to dominate the others, then a trade-off or aggregation problem must be solved. Another approach might be to reduce the number of criteria or weight of their relative performance. There are many approaches that might be taken by an analyst, but the important consideration at this stage of developing system effectiveness is to identify and address the appropriate objectives.

The objectives are related to several different categories which may or may not be mutually exhaustive depending on the scope of the evaluation effort (Figure 10). Some of the objectives can be related to air defense doctrine which states that the air defense mission is to destroy, nullify or reduce the effectiveness of enemy offensive air efforts to a level permitting freedom of action for friendly forces. These doctrinal statements, although general in nature, are reflected in the framework of Figure 10 and are applicable to all air defense evaluations in some degree. However, other categories contain objectives which are not derived from doctrine but are obtained from implicit considerations associated with system missions and objectives.

Earlier when system effectiveness was discussed in general the translation of mission requirements into a set of system objectives included both implicit and explicit requirements

SYSTEM MISSION

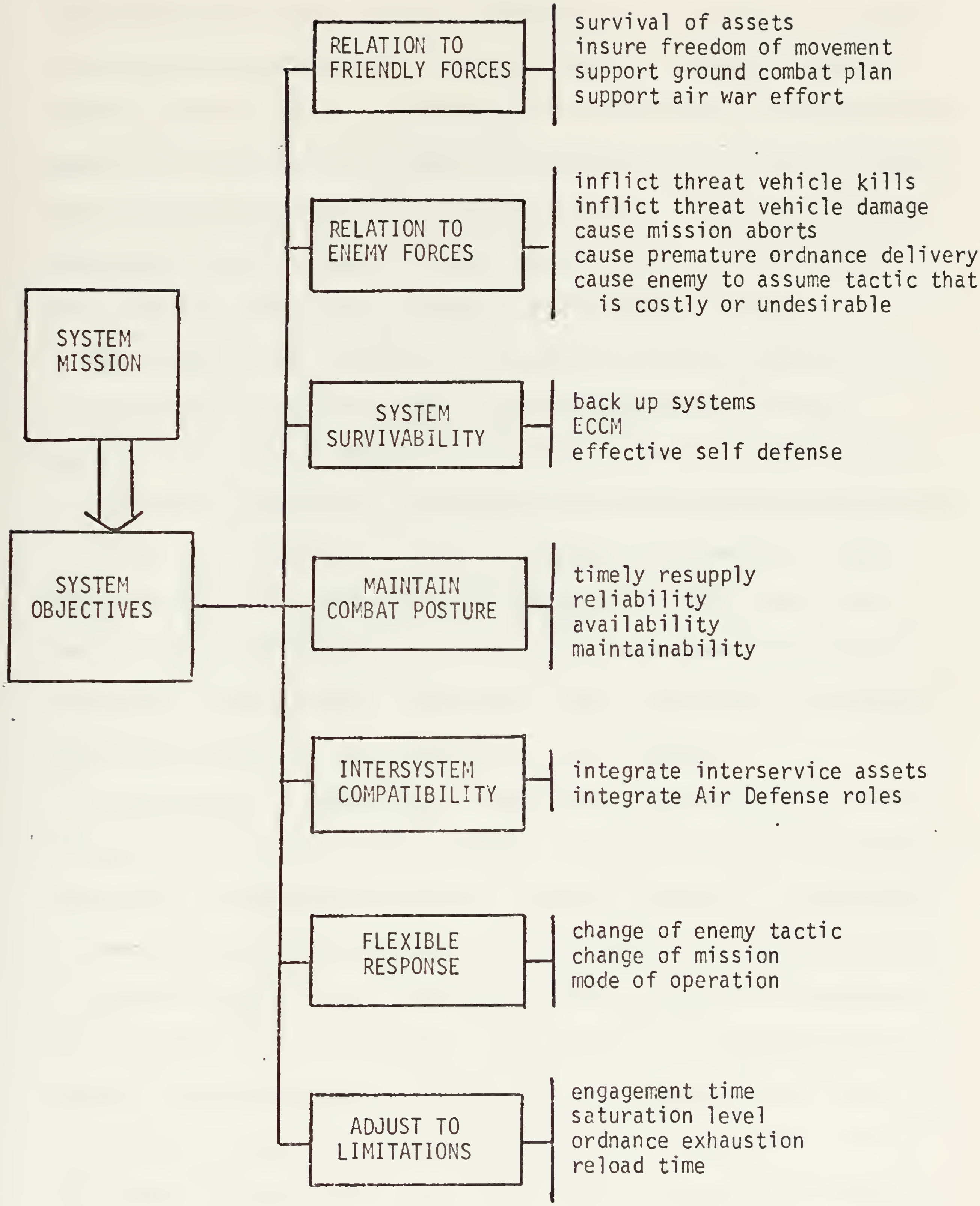

Figure 10

associated with the mission. The explicit requirements are generally those which include objectives in relation to enemy forces and in relation to friendly forces. These are essentially a more precise restating of the doctrine considerations. Examples of this, from Figure 10, would be inflicting aircraft kills and damage as well as mission aborts upon the enemy and supporting the friendly efforts by protecting vital assets and insuring freedom of movement for friendly forces.

The objectives related to compatibility, flexibility and limitations are derived from their corresponding system descriptors. These objectives are included for the purpose of recognizing system problems and difficulties and attempting to reduce or offset the effects of their influence. Often these objectives are implicit requirements that exist as a result of the operational deployment. An example might be the effect on available engagement time that terrain masking causes by virtue of the deployment of a system.

Maintaining a continuous combat posture is a combination of explicit doctrine and implicit requirements and is a key objective in system evaluation. Combat posture is composed of several elements including the reliability, availability and maintainability of a system. These are valid considerations because of the ability they provide an analyst to be precise when evaluating a system. It is possible to talk in terms of fire units in a system that are fully operational, those that are degraded and others that are non-operational,

instead of relying on a single number which relfects the total number of pieces of equipment.

Precisely stated objectives, combined with the system definition and description, form the basis of the qualitative effectiveness concept needed to operationally define system effectiveness for an evaluation.

If, for example, the air defense system was the Air Defense Brigade, including high, medium, and low altitude fire units, and the stated objective was to protect friendly assets from enemy air attack, then a basis would exist for the development of a qualitative effectiveness concept for air defense. It might be stated as the degree of protection from enemy air attack provided to friendly combat forces and key assets with the designated area of brigade responsibility.

It should be pointed out, when considering the system objectives for an air defense evaluation, that the requirement for air defense assets to support both the air war and ground combat indicates that the objectives must necessarily be determined at a large aggregated combat system. The objectives assigned interceptor aircraft, in the conduct of the air war over friendly forces, are determined by the Tactical Air Force which corresponds roughly to an Air Defense Region. When objectives are determined at this level it might appear that less than adequate support exists for the ground combat plan when air defense assets are assigned to lower level combat forces. However the resultant effect is the avoidance of suboptimization. This raises the question of whether or not

air defense systems should be operationally evaluated at the lower organizational levels. This question is discussed further in Section VI.

C. THREAT

It was mentioned earlier that conflict, by definition, implies opposing forces. Therefore the threat which opposes the system must be developed to assess system effectiveness. The threat must be accepted as an element of the evaluation that is surrounded by uncertainty, because although it may be based upon intelligence information, judgement is always exercised with respect to its appropriateness. The threat is developed in terms of the objectives forces and tactics of the enemy because these are the basic elements of a tactical scenario which is needed for an evaluation (Figure 11)[Ref. 17].

The threat allows the analyst to generate, through the tactical scenario, the enemy penetrators (targets) that will test the ability of the air defense system to protect friendly assets and to influence their survival.

There are other elements which can be used to develop the threat but most of them could generally be categorized within one of the elements of Figure 11.

The target objectives may generate flight profiles to be flown through the air defense system and may determine where and how the enemy aircraft will suppress the air defense assets or avoid defensive strong points by indirect avenues of approach. By considering target priorities, desired

THREAT FACTORS

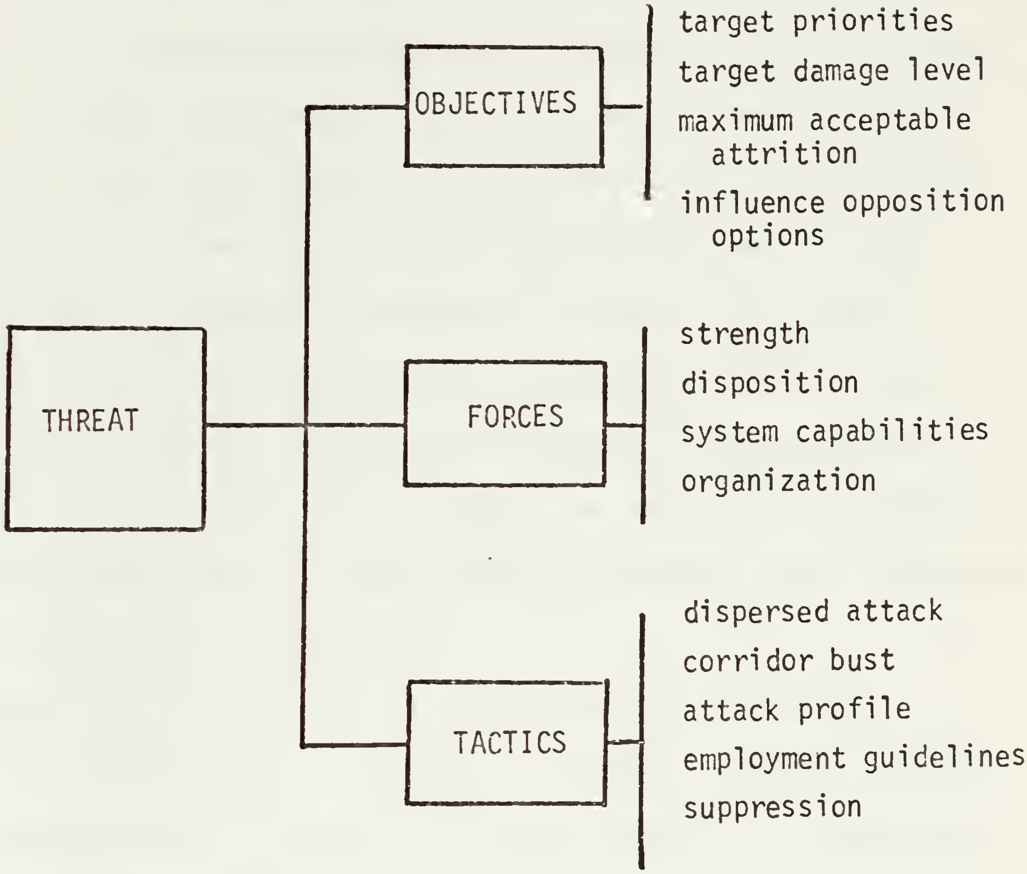

Figure 11

damage levels, the maximum acceptable attrition and the enemy desire to influence our own actions, enough information should be available to provide a selective set of reasonable enemy objectives to the analyst for evaluation work.

The force considerations that are needed will depend on the level at which the selected system is evaluated, but in general the strength, deployment and organization of enemy systems and their associated capabilities are necessary information to provide a reasonable set of possible threat situations. One of the more important considerations involves the threat tactics since an air defense evaluation is usually developed around a friendly defensive posture. For this reason enemy tactics and employment guidelines are of great importance since the set of attack options and associated tactics will have a significant effect on the overall evaluation. Again, wargaming can help identify which attack options and tactics should be considered.

Development of threat for an evaluation is then the combination of objectives, forces and tactics. These in turn may be translated into penetrator flight profiles, generation of penetrators, and avenues of approach which are inputs into assessment models. The information is then translated judgementally and quantitatively into a set of combat options with which the system to be evaluated must contend. This is part of the process of developing an operational definition of system effectiveness.

If the objective for the friendly air defense system is to protect friendly assets, and if the enemy objective is to "win" the ground conflict and the destruction of friendly assets such as ammunition supply dumps, airbases, headquarters, etc. are a means to this end, then air defense system effectiveness would be made operational by formulating specific avenues of approach (A, B, and C) flight profiles (a, b, c), aircraft types (1, 2, 3, 4) and target priorities (air bases, armor, air defense, headquarters). This information, when quantified (weighted, ranked, stochastically conditioned, etc.) and incorporated into the tactical scenario provides the set of enemy combat options to test the air defense system.

One study which was successful in the threat development for an evaluation was the <u>Air Defense Evaluation - 1980</u> [Ref. 39]. This study developed in detail the threat systems, their capabilities and the employment of those systems in a projected threat situation. The result was a well defined set of combat options based upon quantitative enemy system information and judgemental threat considerations which allowed a detailed analysis of friendly system requirements.

D. COMBAT ENVIRONMENT

The last evaluation requirement is the development of the combat environment. The environment in which the conflict takes place is important in an evaluation context for two reasons. First the combat environment together with the

system description will enable the analyst to determine the operational system states. The environment, in general, and weather, ECM, terrain and support, in particular, affects the system states. Second, the combat environment is needed together with the forces and mission as a key element of the tactical scenario which drives the evaluation effort. There are many elements which contribute to the combat environment most of which logically fall into one of the categories of Figure 12. The economic factors and nature of conflict are usually determined at a level beyond the evaluation, but the effect of these elements can be significant in the evaluation. An obvious example would be the consideration of a nuclear environment which would lead to different tactics and troop dispositions; likewise the consideration of a valuable resource could influence the environment.

When a combat environment is usually given consideration the primary emphasis is on weather and terrain because of the masking and mobility effects of terrain and the degraded operation of many systems in adverse weather. But air defense evaluations must be concerned even more with the effects of ECM/ECCM whether it originates from an airborne or ground based system. No enemy capable of generating a potent air attack will risk the loss of costly and sophisticated aircraft in a benign tactical environment. If air defense systems are present in the conflict; it should be assumed that the enemy will employ ECM/ECCM on a massive

COMBAT ENVIRONMENT

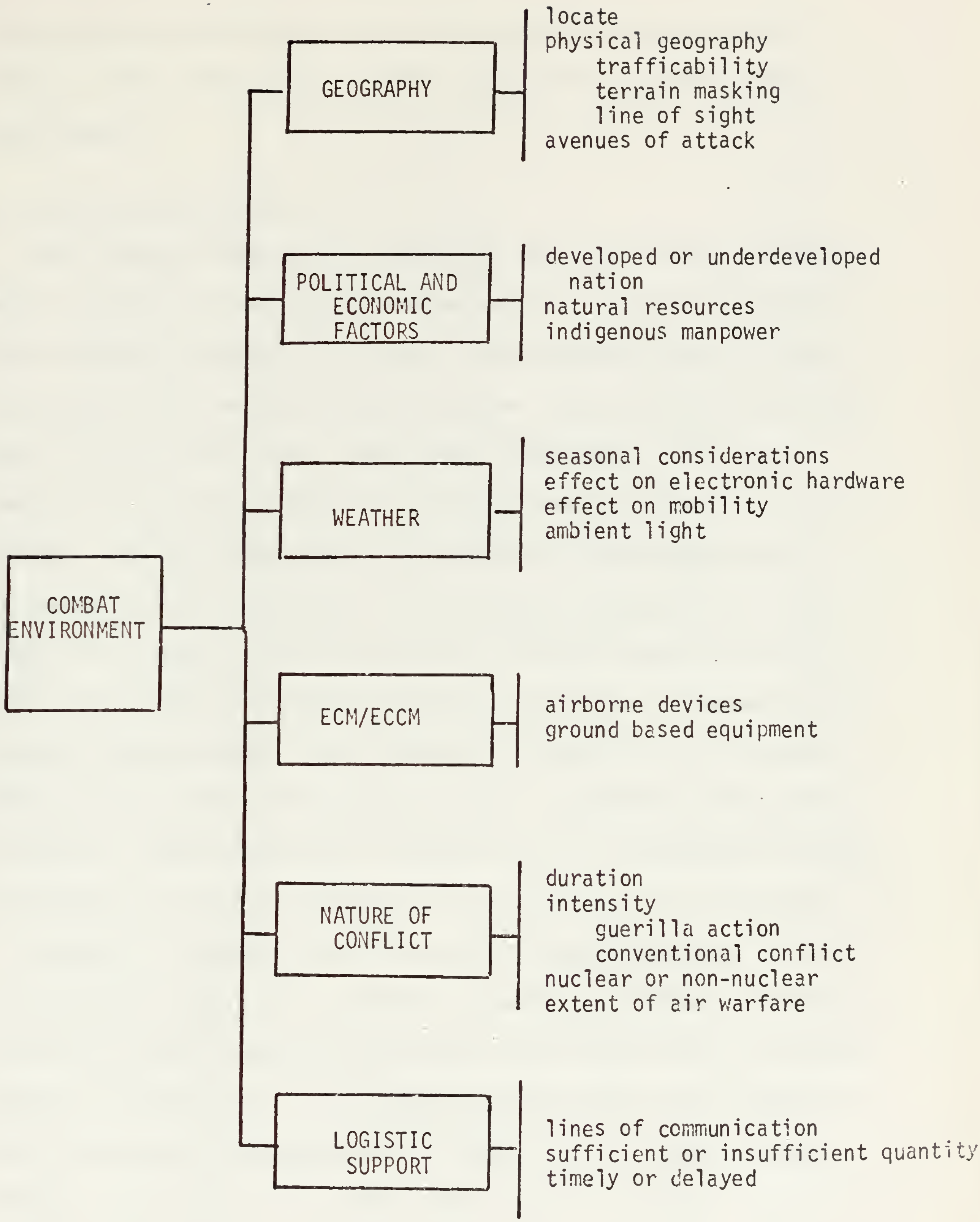

Figure 12

level and an evaluation of an air defense system should reflect this assumption in the development of the combat environment.

E. EVALUATION PROCESS

The combat forces, the missions and the combat environment provide the necessary elements of a tactical scenario. The tactical scenario, in turn, may be considered to operationally define system effectiveness: the scenario provides what is to be observed, under what conditions, and the operations to be performed. How the observations are to be made and how they are to be measured and handled must be included in the system effectiveness evaluation. Combining the results of an assessed tactical scenario with selected measures of effectiveness yields an assessment of system effectiveness. The conflict results of a tactical scenario can come from several means, including parametric analysis, system indices, deterministic or stochastic models and finally from the judgement of the analyst or the user.

Figure 13 depicts graphically the main elements of the evaluation process; the system, objectives, threat and combat environment generate possible operational and non-operational system states. The combat environment also combines with the threat information to form a set of enemy combat options to exercise in opposition to the friendly system. From the non-operational and operational states, reliability, availability and maintainability parameters are developed

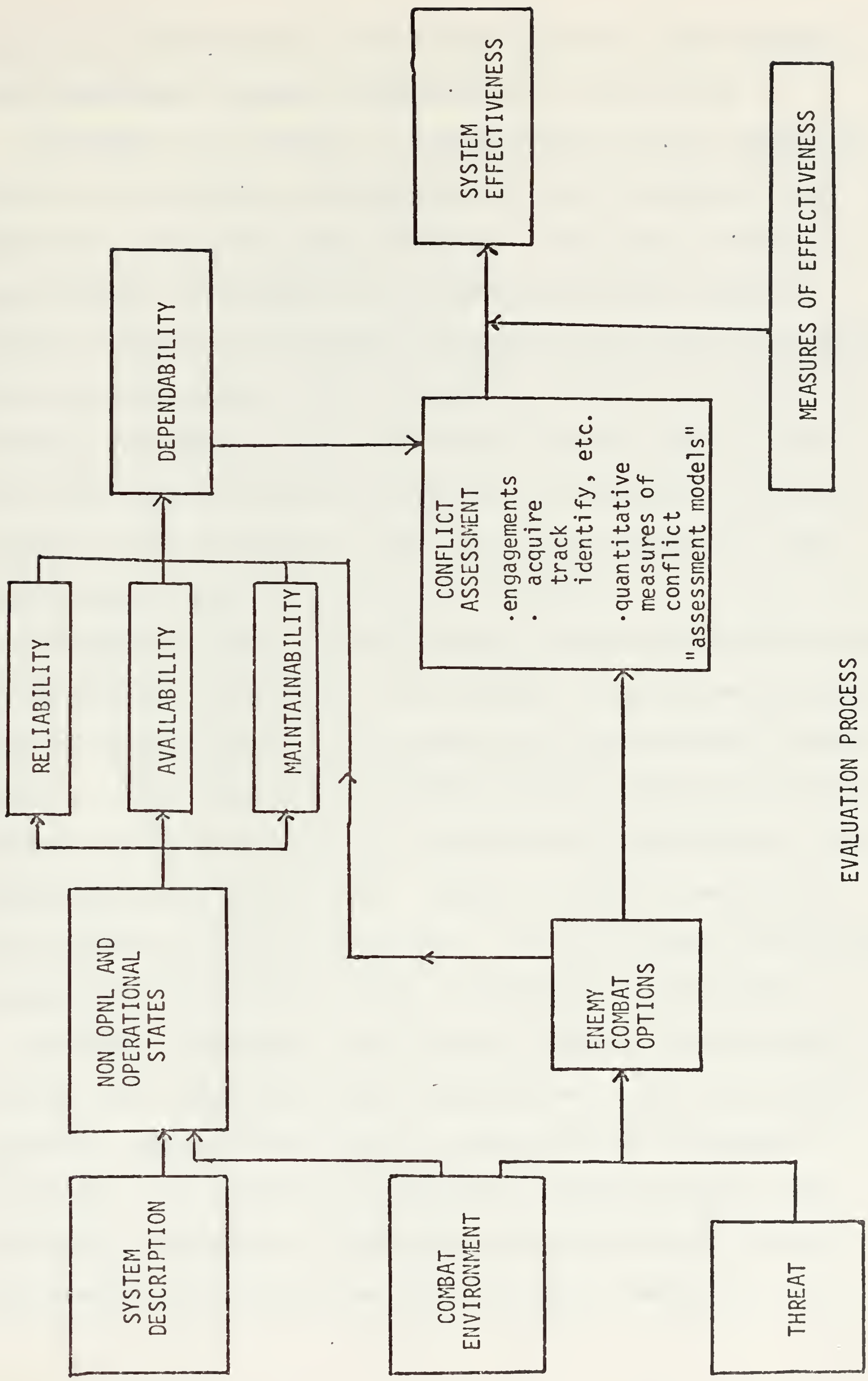
EVALUATION PROCESS
SYSTEM DESCRIPTION
COMBAT ENVIRONMENT
THREAT
NON OPNL AND OPERATIONAL STATES
ENEMY COMBAT OPTIONS
RELIABILITY
AVAILABILITY
MAINTAINABILITY
DEPENDABILITY
CONFLICT ASSESSMENT
.engagements
. acquire
track
identify, etc.
.quantitative
measures of
conflict
"assessment models"
MEASURES OF EFFECTIVENESS
SYSTEM EFFECTIVENESS

Figure 13

and when influenced by enemy combat options, which degrade the parameters, system dependability is formulated.

Consider as an example a theater-level combat operation in which air defense, ground forces, and interceptors are opposed by attacking enemy aircraft. The ground forces are deployed tactically in a defensive posture, the air defense assets are uniformly distributed and the interceptors are on runway alert. The air defense effectiveness concept is the protection of friendly assets and the enemy, using a low flight profile has the objective of destroying selected targets while advancing on two avenues of approach. The combat environment is benign (no ECM/ECCM).

Following Figure 13, the system (theater-level air defense) is selected and described. The threat is also developed and in conjunction with the environment the enemy combat options stated. Knowledge of the friendly system allows development of the system states and the reliability, availability, and maintainability information. Assume for this example that all systems are fully operational. At this point the tactical scenario is begun and conflict assessment is initiated.

Conflict assessment may include a series of assessment models which evaluate target acquisition, tracking, identification, deception and other elements of an engagement. Assessment also involves bookkeeping, which includes such measures of conflict as the number of subordinate systems suppressed or destroyed, surviving assets, damage to the

system, enemy aircraft killed, damaged or diverted and other measures that describe the conflict.

The work that Braddock Dunn and McDonald, Inc. has done with its Tactical Air Defense Computer Operational Simulation (TACOS) is a good example of conflict assessment [Ref. 5]. TACOS utilizes a highly modular approach to portray the critical events and system interactions. The output of the conflict assessment is a battle history and a summary of the conflict statistics.

Returning to the example on page 65 assume the enemy attacks on the two approaches and is engaged by low altitude air defense assets. The enemy has achieved local superiority by concentrating his forces but the attrition forces the attackers to a medium altitude profile. The attack aircraft are passed through air defense channels to a medium altitude missile system, indicating successful control and coordination. At the same time interceptors are scrambled and vectored toward the enemy aircraft. Upon interceptor arrival the missile units transfer the mission to the interceptors, resulting in an additional interface success and the destruction of the remaining attackers.

The battle history of this example provides a great deal of information concerning the effectiveness of the air defense system. Local defeat (saturation of these air defense systems) did not adversely affect the friendly forces theater-level operations, hence we might assume tentatively that the right

system was selected. The appropriate relationships between friendly and enemy actions were depicted, and the interfaces and interactions among complementary subsystems were accounted for in this example.

Conflict assessment results provide quantitative information which must be handled and treated in such a way that the effort supports the goal of system evaluation. The quantitative results are an indication of how the system performed in combat, but more information is needed when system effectiveness is sought. If the system effectiveness is the extent to which the system attains a set of objectives, then a quantitative expression of assessment results as the extent of attained objectives is what we desire; this is called a measure of effectiveness.

If in the previous example, the fraction of surviving friendly air defense assets was chosen to be the measure of effectiveness then the system effectiveness for this iteration of the evaluation would be maximized.

Measures of effectivenss were discussed earlier in terms of their development from doctrine and from system objectives where an attempt is made to quantify a qualitative effectiveness concept. The selection of measures of effectiveness is one of the most important steps in an evaluation and could easily be considered as a separate problem for study. It is particularly important in an air defense evaluation since the analyst is often faced with multiple measures of effectiveness. There is rarely a single criterion or a common

denominator for air defense evaluations. Hence, in such an evaluation effort a choice must be made selecting those measures which accurately reflect the effectiveness of the system being evaluated. Rather than approach measures of effectiveness from a theoretical basis, a few heuristic arguments related to air defense evaluation should emphasize how critical this step is.

While much attention is given the problem of suboptimization in studies, the selection of the wrong measures of effectiveness can have equally disastrous effects by focusing on the wrong effectiveness criteria. The results may vary from not answering the original question but a different question to not answering any question at all. A classic example of using the wrong measure of effectiveness is contained in Methods of Operations Research [Ref. 27], where Morse and Kimbal discussed the case of British merchant vessels in the Mediterranean that were subjected to damaging aircraft attacks in World War II. When the ships were equipped with antiaircraft guns it was observed that in only 4% of the air attacks was the plane shot down. Serious consideration was given to the possibility of removing the guns to employ them where they were needed more and could be used more effectively. Closer observation revealed that the original purpose of the guns was to protect the ship, not to shoot down attacking aircraft. When the situation was measured in terms of a ship surviving an attack with

less damage than an unarmed ship, the guns were considered extremely effective.

This historical example, in the context of modern air defense systems, reinforces the point that aircraft kills is a poor measure of effectiveness if the mission and objective of the system is to protect friendly assets. There are many additional ways an asset might survive other than as the result of an aircraft kill: enemy mission abort, undesirable attack profile or less effective ordnance delivery.

Another consideration for measures of effectiveness is the manner in which they are aggregated or weighted in terms of their importance. In the case of a single criterion this presents no problem. However when dealing with many measures of effectiveness it is important to identify those which are the most critical in determining system effectiveness. Often the identification or selection is a judgement that is made by those performing the evaluation. In other cases expert opinion is considered or the decision maker is asked which measures are most important. Many means of selection might be used and one example would be the use of the method of successive intervals [Ref. 37], where subjective values of attributes given by individuals can be developed into an interval scale relationship providing rank order and unit of measure. This tool would be particularly useful in an air defense evaluation where the evaluations of many

could be ranked by this method; the unit of measure would also provide information on how much more important one measure might be than another. Whatever means might be used to select the appropriate measures of effectiveness it is often the most important decision in analysis and should be allocated a commensurate amount of effort.

When determining overall system effectiveness it is desirable to develop an effectiveness function which will yield a meaningful measurement of system effectiveness for an alternative which may be compared to others; or to compare several alternatives at the same time. An important consideration at this point is the system that is being evaluated. If the system is defined to be a battery or fire unit then the WSEIAC scheme might produce the results desired, but if the system operates at a level such as the Air Defense Region or theater level then nature's options, the enemy options and the defensive effectiveness interacting with the enemy and nature must be considered in terms of aggregated measures of effectiveness. Evaluations at aggregated levels are normally complex, in which case the important measures of effectiveness should be selected, aggregated and combined with the battle histories or assessment information to achieve an indication of system effectiveness.

Additional consideration should be given to the level of detail that system effectiveness provides. If the assessment results are generated in significant detail, then care

should be taken so that effectiveness functions will not be over-simplified. Likewise, general results should not be displayed or transformed into system effectiveness through analytical overkill. As an example consider assessed results that are prepared in great detail; if this information is translated into a binary decision variable, then the informative content of that data is lost and the evaluation may be misleading. Likewise, it is also misleading to express effectiveness results in greater detail than the study can support.

In determining and displaying system effectiveness, the overriding consideration must be whether or not the process provides a comparison of alternatives to assist the decision-making effort. This judgement is obviously more accurately determined by hindsight, but the essential question should be addressed by the analyst simply asking himself what information, concerning the system, does this evaluation provide?

V. DIFFICULTIES OF EVALUATION METHODOLOGY

The system effectiveness methodology developed for air defense has certain factors which are of interest in an evaluation but are difficult to include and handle. One of the most difficult factors is the interface of other systems, where an overlap of responsibilities or capabilities requires coordination and control of the systems to avoid over-allocation of assets in some areas and to avoid leaving other areas deficient in defensive capabilities. Command, control and communication (C^3) is a critical area which deserves attention in operational defense exercises, and remains a problem area in the current state-of-the-art. An example of a key interface is the Air Defense-Air Force boundaries in a defensive posture. The low altitude Air Defense assets operate primarily by themselves and coordinate with ground forces rather than the Air Force. However, medium and high altitude assets in an air defense system are under the operational control of the Air Force. Effective control and allocation of effort is a complex task in reality and equally so in an evaluation effort. Consider the control of vectored interceptors and alerted missile units operating against penetrating aircraft, where a decision must be made to hold the missile engagement and continue with interceptors or to redirect the interceptors and allow the missile units to engage. This is clearly a case of overlapping responsibility

where the interface of friendly assets must be controlled to prevent excess expenditure of ordnance and also damage to friendly aircraft.

Another interface is that of divisional and non-division air defense assets which may be visualized by referring to Figure 7. Low altitude systems assigned to divisions must interface with non-division air defense assets and with the ground forces. While supporting the overall ground plan of operation, the low altitude systems must coordinate with missile units operating in rear areas to provide coordinated defense in depth across organizational and operational boundaries. When dealing with an area as complex as system interfaces, the contribution of field exercises and taped command and control exercises is significant. It provides information that is normally not available, except at great cost, through probabilistic or simulation methods. Analysis of this data can provide information for evaluations that otherwise may not be available.

In addition to interfaces or boundaries as an evaluation factor, the interactions or actions on each other are also considered. This becomes a rather fine distinction in general, but specifically there are asset interactions which contribute to system evaluation. Interactions among air defense fire units are usually well-handled because the operation of these units is well understood. For example, the effect of a unit that is out of action is well defined

in terms of realigned sectors of responsibility, and command and control is designed to provide efficient allocation of fires. But at higher levels where the interactions are between more aggregated systems or even between services, the effect they have on each other is not clearly defined and not easily evaluated.

The interface of interceptors and missiles was discussed as a tactical allocation problem earlier, but an interaction or effect also takes place in such a situation. When interceptors are given priority to engage the missile units must hold their fire, and the time spent waiting may cause the missile systems to engage at less than optimal range or perhaps not at all. Another interaction between these same forces arises when interceptors, due to their flexibility, are used in a distant locale within the system area and cannot respond on short notice to the needs of missile systems for back up support or to drive off enemy suppression aircraft.

Each interaction provides an individual result that may have synergistic or antagonistic effects between the systems. One way of handling these interactions might be to consider them as a set of stylized joint deployments, where the interaction effects may be analyzed separately (for example the antagonistic category of a hold fire command assigned to a missile system to allow intercepter engagement which reduces the available engagement time if the hold fire is lifted).

A relative frequency of the effects might be constructed and a quantitative expression could be developed from Monte Carlo methods.

The interdependence of systems is a key factor in analyzing an evaluation framework, particularly at higher levels of systems. Complex air and ground force systems are composed of highly interdependent sybsystems which all but eliminates distinction between independent and dependent variables. According to reference 34, the analytical task then becomes one of identifying self-contained sets of relationships that can be treated independently. If no such sets exist then the task becomes subjective or judgemental which involves the difficulty of non-quantification of relationships or of justifying a derived quantitative relationship. In some cases the answer is to treat the interdependent systems separately, ignoring the contributions of lesser systems. When this is done the results may be viewed as relative measures, rather than an absolute outcome, subject to the higher order effects caused by lesser systems.

Earlier, uncertainty was discussed primarily in terms of input data which is often reflected in the results of an evaluation. There are other forms that uncertainty may take and according to Hitch and McKean [Ref. 19] the best advice is to include uncertainty, attempting to identify the major areas, and try to reflect them in the analysis. Some of the major areas of uncertainty are the assumptions, the enemy

and his reactions, technological uncertainty, statistical uncertainty and, of course, the human factors associated with the evaluation.

Within the Air Defense methodology the enemy and his reactions are perhaps the most important uncertainty factora, since the enemy options and tactics will vary greatly depending on how effective the friendly defensive systems are at countering the latest combat option. The other element of uncertainty that becomes important is how the air defense system will function under stress. This is an element of great uncertainty since there exists no combat data to support or deny the empirical claim of the industries which produced the systems or the service that generated the requirement for the system.

The advice to include uncertainty can prove to be very costly since the number of cases to analyze and compute increases as the power of the factors that are permitted to vary [Ref. 12]. For example, if there were two uncertain factors and each was permitted to take four values, the number of cases is 4^2 or 16. But if ten uncertain factors were permitted to take four values the number of cases would be over 1,000,000 and the cost constraint would be reached quite rapidly. Clearly, the need to consider all interesting cases must be tempered by the economic constraints and time constraints that apply to a given study.

When discussing how the difficult factors such as C^3, which affect the methodology, should be handled the first

consideration is whether they can be quantified. If so, a determination should be made concerning the advantage or net gain supplied to the evaluation relative to incorporating the factor as a qualification or judgemental consideration.

The next decision would be to determine where within the methodology the difficult factor should be addressed. If the factor is quantified and included as an input the complexity of the evaluation may increase; whereas a factor developed and included as a measure of effectiveness in a qualitative manner may have an oversimplified effect on the evaluation. Consider the effect that a new enemy electronic jammer might have as an uncertain factor. If the jammer was quantified as an input with a wide range of capabilities and included in the assessment portion of the methodology it might have a significant effect on the critical variables such as units suppressed, number of successful penetrations, number of penetrating aircraft lost, number of targets destroyed or other variables. This effect might be reflected in the measurement of system effectiveness but the cost might be prohibitive. If it were included as a constant factor added to the effectiveness measure the cost would be less but the effectiveness value might be disproportionately affected by the term.

Another way to include a difficult factor might be to deal with it as a nominal value or best estimate to be carried through the evaluation. In this way the factor is evaluated

at a lesser cost but if the value is not correct, the factor and any other interdependent factors may have an adverse effect on the evaluation. Sensitivity analysis at the end of the evaluation would be another way to address this problem.

In analyzing this methodology it is important to recognize that there are difficult factors that must be considered, and an air defense methodology will have as many or more of these factors as other evaluations. The best approach is probably that of reference 19; do not ignore these factors but try to identify them and include them to whatever extent possible. How they should be included is a decision that must be based upon consideration of their contribution in relation to the evaluation constraints.

VI. CONCLUSIONS AND RECOMMENDATIONS

It was noted in Sections I and II that improved methodology for evaluating air defense system effectiveness is needed to provide decision makers with a better basis for determining preferred systems and the "best" deployment of these systems. This thesis has investigated the factors upon which air defense system effectiveness depends and has proposed a methodology appropriate for such evaluations.

A key determination in the system effectiveness study process was seen to be the identification of the system to be evaluated. To the unintiated this may appear to be obvious, but case studies (such as Ref. [28]) were considered in which the determination (more precisely, the incorrect determination) was one of the evaluation weaknesses or "lessons learned". This determination is particularly important, since the system determines not only the level at which the threat is considered but also indicates the interfaces and interactions that must be considered within the hierarchy of supersystems and subsystems.

The mission of air defense, in general, is to protect friendly combat assets by neutralizing enemy aircraft. If one views the battlefield as three dimensional and considers the combat options available to an enemy's aircraft and missile systems it is clear that enemy tactics and objectives depend on friendly air defense systems. Additionally, the

friendly air defense system consists of several complementary systems (for example, HIMAD, LOMAD, SHORAD, friendly interceptor aircraft) which function in support of each other. Based on these observations it was concluded that air defense should be evaluated at the theater level. This conclusion also has an heuristic appeal when considering the air battle in relation to air defense systems. Moreover, the need to evaluate at the theater level is apparent when consideration is given to the fact that enemy aircraft might well have the range and combat power to attack objectives anywhere within the theater of operations.

It was discussed that system effectiveness must be made operational (i.e. concrete). The tactical scenario is the vehicle for accomplishing this by considering concrete realizations of enemy threat, friendly and enemy systems, friendly and enemy missions, and the combat environment. Specific weaknesses in the current state-of-the-art exist for the identification and quantification of military objectives. Thus, it is recommended that future research be done on these topics. Because past large system (such as air defense) evaluations have failed to (either explicitly or implicitly) consider uncertainties (such as uncertainties in input data) or to assess sensitivity of study results to variations in input and other parameters, it is also recommended that future research be undertaken in these areas. This research could be accomplished in part by following

Weiss' [Ref. 45] recommendation to maintain a continuous modeling and evaluation activity throughout the life cycle of systems.

Additional topics for further research are the need for more quantitative information about the interfaces and interactions throughout the system hierarchy, particularly C^3, and in the area of conflict termination. Recent conflicts in the Middle East and Southeast Asia indicate that employing integrated air defense systems can reduce the effectiveness of air warfare over ground forces and vital assets. Additional quantitative information concerning interfaces and interactions would contribute greatly to system integration. Conflict termination is an appropriate area for future research because the length of an engagement may affect the objectives that are selected for the system. Short term objectives might be to prevent damage to a vital area, whereas a long term objective might be to inflict a prescribed level of attrition over a period of time.

APPENDIX A. ATTACK-DEFENSE GAME

The advantage of evaluating at a higher system level may be seen by Dresher's game theory approach to Defense of Two Targets Against Attack [Ref. 11]. Suppose that blue, the defender, has two targets t_1 and t_2 of values k_1 and k_2, respectively, which are to be defended against an attack by red. Assume in this case that red and blue are equally strong and have the same number of forces S.

A strategy for red is an allocation of x attackers to t_1 and $S - x$ to t_2, where $0 \leq x \leq S$. A strategy for blue is an allocation of y defenders to t_1, where $0 \leq y \leq S$, and $S - y$ to t_2

	target t_1	target t_2
Value	k_1	k_2
Offensive allocation	x	$S - x$
Defensive allocation	y	$S - y$

Let the payoff to red be proportional to the number of attacking units that reach the target and the target value. The payoff can be described as follows:

$$M(x,y) = \begin{cases} k_1(x - y) & \text{if } x \geq y \\ k_2(y - x & \text{if } x \leq y \end{cases}$$

where k_1 may be called the payoff per attacking unit that penetrates blue's defenses at t_1. Since $M(x,y)$ is a convex function for y for each x, the value of the game is

$$v = \min_{y} \max_{x} \ M(x,y) = \min_{y} \max[k_2 y, k_1(S-y)]$$

The expression $\max[k_2 y, k_1(S-y)]$ is a maximum for $k_2 y = k_1(S-y)$ and blue's optimal strategy $(y^*) = \frac{k_1 S}{k_1 + k_2}$.

Therefore blue would allocate $\frac{k_1}{k_1 + k_2} S$ defensive units to t_1 and $\frac{k_2}{k_1 + k_2} S$ units to t_2.

Solving red's optimal strategy, $M(x, \frac{k_1 S}{k_1 + k_2}) = v$, and this equation gives two solutions:

$$x_1 = 0 \quad ; \quad x_2 = S .$$

Then, $\frac{\partial M(0,y^*)}{\partial y} = k_2$, $\frac{\partial M(S,y^*)}{\partial y} = - k_1$

which provides red's optimal strategy as the function

$$F^*(x) = \alpha I_o(x) + (1-\alpha) I_S(x)$$

where

$$\alpha k_2 + (1-\alpha)(-k_1) = 0 \quad \text{or} \quad \alpha = \frac{k_1}{k_1 + k_2}$$

The solution of the game is explained as follows: the defender splits his forces and may adopt a fixed deployment of those forces; $\frac{k_1}{k_1 + k_2}$ of them at t_1 and $\frac{k_2}{k_1 + k_2}$ of them at t_2. The attacker concentrates his forces on either t_1 or t_2 at random. With probability $\frac{k_2}{k_1 + k_2}$ the attacker chooses t_1 and with probability $\frac{k_1}{k_1 + k_2}$ the attacker chooses t_2.

If red (attacker) is chosen to be enemy aircraft and blue (defender) is designated as air defense systems, the advantage of evaluating at the higher level becomes apparent. The defending forces deployed at t_1 and t_2 will be engaged by all or none of the attacking aircraft depending on red's random selection of a target. If the system were evaluated at one target (subsystem level), say t_1, the blue forces would either be completely effective (because red attacked t_2) or be ineffective (because red overloaded the system at t_1).

By considering the conflict at a higher level the observer (analyst) has the advantage of a more realistic view of the evaluation. By allocating optimally blue accepts the fact that red can locally saturate the air defense system, but blue prevents red from achieving several areas of saturation by selecting a proportional defense and provides the target with maximum defense subject to tactical constraints. Allocation of forces in this manner is referred to as an application of the "no soft spot" principle, which is further investigated by References 7 and 8. This implies that air defense has

weaknesses of being vulnerable to local (subsystem) saturation, but when considered at a higher level the overall defensive allocation is optimal.

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